ARL 153

LIMITATIONS IN DETECTION OF CELESTIAL BODIES EMPLOYING ELECTRONICALLY SCANNED PHOTOCONDUCTIVE IMAGE DETECTORS

RADAMES K. H. GEBEL

SOLID PHYSICS RESEARCH BRANCH

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RADAMES K. H. GEBEL

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FOREWORD

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ABSTRACT

Theoretical limitations in the detection of celestial bodies by means of photoconductive sensors are investigated. Applicable simplified basic equations are derived for the maximum apparent magnitude number of a celestial body that is detectable with the commercially available vidicon tube, (a) assuming the most optimistic conditions and (b) as determined by background radiation during the day and the night, load resistor noise and other practical limitations. The equations are extended to cover the possible gain in sensitivity obtainable by using preamplification with additional image converter type tubes, and by integration over several scanning fields. The schematics of an easily constructed very sensitive experimental vidicon system used for the investigation are appended.

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List of Symbols

A_V Illuminated area in mm^2 of vidicon face plate.

B_B Brightness of the sky in foot-lambert.

E Illumination in footcandle at the focal plane of a telescope.

E_D Necessary input illumination in foot-candle to produce photo-emission equivalent to the photocathode dark current emission.

E_I Illumination in footcandle of vidicon face plate, if intensifier is used befor vidicon.

E_q Energy in ergs of one quantum of light.

E_V Illumination in foot-candle of the vidicon face plate.

I Current in Amp through vidicon target electrode load resistor as result of illumination on face plate.

I_B Current in μ A through load resistor caused by the radiation from the luminescent sky background.

I_D Vidicon dark current in μ A.

I_N Sensitivity of vidicon in μ A per μ W.

K' Boltzmann s constant in joule/degree = 1.38×10^{-23} joule/degree.

M Apparent magnitude number of celestial body.

M_B Limiting apparent magnitude number of celestial body that can be detected in the daytime, taking dark current into consideration.

M_B' Same as M_B but neglecting dark current.

M_g Gain in limiting apparent magnitude number M_L because of preamplification V_I before vidicon.

M_L Limiting apparent magnitude number of celestial body determined by inherent noise of vidicon target electrode load resistor, using a telescope with a given optical system.

M_L' Same as M_L but for a telescope with a different optical system.

M_{opt} Limiting apparent magnitude number of celestial body with intensifier before vidicon under optimum conditions.

M_t Limiting apparent magnitude number where radiation of celestial body is producing an average of one electron for each resolution element covered by the star image during one scanning frame.

M_V Limiting apparent magnitude number of celestial body that can be detected by neglecting all other noise factors, except vidicon dark current.

P_i Number of integrated frames at storage reproducer.

Q_B Average number of quanta of light per mm^2 sec focused onto the intensifier photocathode as result of sky background radiation.

Q_M Average number of quanta of light per sec in focal plane of a given telescope as a function of apparent magnitude number of a celestial body.

Q_V Average number of quanta of light per second focused onto the vidicon face plate causing e_V.

R_C Number of effective resolution elements of the vidicon onto which the image of a celestial object is focused.

R_I Selected number of resolution elements per mm^2 of intensifier photocathode equivalent to effective resolution elements of vidicon target section.

R_L Target electrode load resistor value in Ω .

R_V Number of resolution elements scanned during each frame.

T Temperature of load resistor in degrees Kelvin.

V_I Light flux gain of image intensifier.

V_N Summation of all noise voltages at input terminal of video amplifier.

V_R Noise voltage due to load resistor.

V_S Momentary signal voltage appearing across load resistor.

Z Coefficient of signal to noise improvement as result of P_i .

c Velocity of light in micron per second.

d_T Effective diameter in meters of telescope lens.

d'_T	Diameter of telescope for which M'_L was computed.
e_D	Average number of electrons constituting the dark current occuring for any resolution element for the time the scanning beam appears to remain on one resolution element.
e'_D	Average number of electrons per sec constituting the vidicon dark current.
e_S	Average number of electrons flowing through load resistor from each scanned effective resolution element during the time the beam remains on one element as a result of exposure to radiation from a celestial body.
e_V	Average number of electrons per sec resulting from quanta flux Q_V focused onto the vidicon face plate.
f_L	Horizontal scanning line frequency per sec.
f_r	Number of vertical scanning frames per sec.
f_T	Effective focal length in meter of telescope system.
f_Δ	Video amplifier bandwidth in sec^{-1}.
h	Planck's constant = 6.625×10^{-27} erg sec.
i_S	Momentary signal current in Amp.
p	Probability for detection of the effect of absorbed energy.
q_V	Average number of quanta of light at focal plane for each resolution element during one scanning frame.
t_e	Effective exposure time for photocathode of intensifier used in conjunction with vidicon.
t_f	Time interval in seconds it takes the scanning beam to return to the same resolution element.
t_V	Time in seconds the scanning beam appears to remain on one resolution element.
δ_C	Ratio between average number of electrons flowing through load resistor as result of radiation from celestial object and standard deviation in the number of electrons in the dark current.

δ_I Ratio between the average number of electrons caused by radiation from a celestial body and the standard deviation in the emission caused by background radiation plus photocathode dark current emission per effective resolution element of the intensifier photocathode.

δ_{SN} Signal to noise ratio = ratio between vidicon signal voltage and noise voltages.

η_C Quantum efficiency of photocathode of intensifier used before vidicon.

η_I Efficiency factor for coupling intensifier reproducer phosphor screen to vidicon face plate.

η_P Effective quantum efficiency factor of vidicon = ratio between average number of electrons flowing through the load resistor as a result of radiation focused on the face plate of the vidicon and the average number of quanta of light constituting that radiation (for a light with a wide spectral distribution).

η_P' Same as η_P but for monochromatic light.

η_T Transmission efficiency of telescope system.

λ Wavelength of monochromatic light used for determining η_P .

INTRODUCTION

The purpose of this paper is to treat some of the limiting conditions operative when using an image pick-up tube which has a photoconductive sensing element, (vidicon) for detection of the visible radiation from celestial bodies. The increase in sensitivity that can be obtained, by using image intensification between the optical system and the photoconductive sensing element of a vidicon, is also treated. For those readers not familiar with vidicon techniques, a short explanation is included of the mechanisms of detection and scanning. Since we are dealing with general performance possibilities and limitations, simple equations are used, neglecting factors of minor importance. Some of the performance limitations represent theoretical values unlikely to be achieved in practice; these may be used as goals in this field of endeavor, while serving to prevent waste of effort on impossible objectives.

ENERGY CONVERSION AND SIGNAL GENERATION IN A VIDICON

The vidicon may be considered as divided into three sections: the electron gun section, scanning section and target section. (Figure 1). The electron gun section has a thermionic cathode and associated grids, to produce and focus the electron beam, which will scan the photoconductive layer of the target section. The scanning is accomplished by conventional deflection circuits, either magnetic or electrostatic. The target section consists of the signal electrode which is a transparent metallic coating, deposited on the inner surface of the optically flat transparent glass face plate of the tube, and the target film, which is a thin photoconductive layer (often $Sb_2 S_3$) deposited in turn on the metallic coating. In the operation of the vidicon the target film and the signal electrode act as a capacitor shunted by the resistance of the photoconductor, with the signal electrode forming one plate of the capacitor (front side) and that surface of the photoconductor toward the electron gun forming the other plate (back side). The photoconductive target layer is a continuous semiconductive film which is not divided into separate resolution elements as is the case of the photocathode in the iconoscope. Nevertheless the target film acts almost as if it consists of separate resolution elements, because of the chosen scanning rate and the selected thickness of the photoconductor (usually in the order of 5 to 10μ), which result in a high lateral resistance. Therefore, in the following, for simplicity, the target film will be assumed to consist of separate resolution elements. Each resolution element acts as a capacitor shunted by the transverse resistance of that particular resolution element of the photoconductor. The effective size of a resolution element will depend on the scanning beam and other design factors.

The signal electrode of the target section is supplied with a positive potential, in respect to the thermionic cathode, that is below the first crossover potential, resulting in a secondary emission yield of less than unity when the scanning beam hits the photoconductive target film. If no scanning beam is present, the potential of the signal electrode and the side of the photoconductor toward the electron gun will be equal because of the finite transverse conductance of the semiconductive layer. The conductance between the front and back side of each resolution element depends on the amount of radiation focused on the film, and usually increases with the intensity of the radiation. If a low velocity electron beam of sufficient strength is operated to scan the back side of the target film the potential of the spot where the scanning beam impinges is brought from its previously positive value, which was determined by the potential on the signal electrode, down to approximately the cathode potential. Then the maximum potential difference between front side and back side of that resolution element exists. After the scanning beam has been moved on, the potential of the back side of the resolution element, which was brought down to cathode potential will increase toward the positive potential of the signal electrode; which means that the charge held by the resolution element is discharging through its transverse conductance. The positive potential of the back side of a resolution element of a photoconductor cannot exceed that of the front side; it can only approach the potential of the front side through discharge due to the photoconductance of the element. The amplitude of the electrical signal produced by the vidicon is a function of the positive potential of the back side of the photoconductor; thus establishing a maximum amplitude regardless of the brightness of the illumination. This gives the vidicon an important advantage over many photoemissive arrangements in the

presence of very bright point sources. For example, in the image orthicon, under threshold conditions, high intensity point sources may produce halation effects because of insufficient neutralization of the target plate and prevent the detection of very faint stars in the neighborhood of a much brighter celestial body.

The potential of the back side will approach that of the front side exponentially as a function of time and the momentary potentials are determined by the capacity and the conductance of the particular resolution element. Since the conductance of each resolution element is a function of the amount of radiation focused onto it, the scanning beam will see a potential pattern corresponding to the intensity pattern of the radiation focused onto the target film, provided that the scanning beam return time is kept short enough to keep the back side from approaching the potential of the front side. When the scanning beam hits the back side of the target film, the resolution elements, each of which acts as a capacitor, will charge, and a current will flow through the load resistor R_L (Fig 1). The current will nearly cease if the scanning beam remains on a resolution element long enough to bring its back side to cathode potential. The initial intensity of this current, as the scanning beam hits a resolution element, depends on the positive charge potential the resolution element has with respect to the cathode. In the further mathematical treatise, we shall neglect any current decay occurring during the charging of a resolution element and deal only with the integrated value. As the scanning beam moves over the resolution elements, the variation of the scanning beam current and consequently the current through the load resistor corresponds to the potential pattern on the back side of the elements and, therefore, to the intensity of the image pattern focused onto the vidicon face plate. Bringing the back side of a resolution element down to

cathode potential does not result in removal, or erasure, of the photoconductance resulting from the radiation focused onto the face plate of the vidicon. In a conventional vidicon operated at high light levels, decay of the photoconductance, which means that after the radiation has been removed nearly all the electrons which have been brought to the conduction band are returned to the valence band, usually occurs in a fraction of the time used for scanning one frame. On the contrary, the conventional storage vidicon, which permits continual read out of the information for several seconds after the illumination has been removed, uses a photoconductor for which it takes a large multiple of the scan time for the electrons to return from the conduction band to the valence band.

THE LIMITATIONS OF THE VIDICON

The quantum efficiency for photoemitters is usually defined as the ratio of the number of electrons emitted because of absorbed radiation to the number of quanta of light focused onto the photoemitter; for photoconductors with electron mobility this would correspond to the ratio of the number of free electrons found in the conduction band because of absorbed radiation to the number of quanta of light focused onto the photoconductor. However, in this paper, for practical reasons, we shall define as the "effective quantum efficiency" the ratio of the number of electrons comprising the current which is obtained by utilizing the photoconductance to the number of quanta of light focused onto the photoconductor. In the case of the vidicon this is the ratio between the number of electrons flowing through the load resistor because of the scanning action and the number of quanta of light focused onto the face

plate. Then if we use Q_V to denote the average total flux of quanta of light per second focused on the face plate of the vidicon, t_f for the time interval in seconds for the scanning beam to return to the same resolution element again, and e_V for the average of the total number of electrons per second constituting the current caused to flow through the load resistor by the scanning action, we may write, for the effective quantum efficiency, η_P in electrons per quantum of light, of the vidicon,

$$\eta_P = \frac{e_V \; t_f}{Q_V \; t_f} = \frac{e_V}{Q_V} \tag{1}$$

For a 2870°K light source one foot-candle corresponds to approximately 1.7×10^{12} quanta of light per mm^2 sec with wave lengths in the range between 0.29μ and 1.5μ and, since one Amp = 0.624×10^{19} electrons per sec, we may rewrite Eq (1)

$$\eta_P \approx \frac{0.624 \times 10^{19} \; I}{1.7 \times 10^{12} \; E_V A_V} \approx \frac{3.7 \times 10^{6} \; I}{E_V A_V} \tag{2}$$

where A_V is the illuminated area in mm^2 of the photoconductor, E_V is the illumination in foot-candles of the face plate of the vidicon, and I is the current through the load resistor resulting from the illumination of the face plate.

Figures 2 and 3 show the light transfer characteristic curves of high quality vidicons, the Machlett ML 7351, which has an exceptionally low dark current, and the RCA 7263. The dark current of vidicons is mainly a function of the material used for the photoconductor and its dimensions, the face plate temperature and the voltage applied to the signal electrode. Thus a given dark current can be obtained by proper
proper

adjustment of the target potential (Figure 4). Then, using Eq (2) and referring to Figure 2, we find for the ML7351 tube, when operating with 30 fields per sec, a dark current of 0.08 μ and 0.1 foot-candle illumination on the face plate,

$$\eta_P \approx \frac{3.7 \times 10^6 \times 0.18 \times 10^{-6}}{0.1 \times 120} \approx 0.055 \approx 5.5\ \% \tag{3}$$

and for a dark current of 0.02 μ A we find

$$\eta_P \approx \frac{3.7 \times 10^6 \times 0.1 \times 10^{-6}}{0.1 \times 120} \approx 0.03 \approx 3\ \% \tag{4}$$

It is of interest to determine for monochromatic light the effective quantum efficiency η_P'. Since $E_q = \frac{hc}{\lambda}$ where E_q is the energy of one quantum of light in ergs, h is Planck's constant and is equal to 6.625×10^{-27} ergs second, c is the velocity of light in microns per second, and λ is the wavelength of light in microns, we may write for η_P'

$$\eta_P' = \frac{0.624 \times 10^{13}\, I_N}{\frac{10}{E_q}} = \frac{0.624 \times 10^{13}\, I_N}{\frac{10}{h \frac{c}{\lambda}}} \approx \frac{1.2\, I_N}{\lambda} \tag{5}$$

where I_N is the sensitivity of the vidicon at λ in μ A/μ W (1 μ Watt = 10 erg/sec) and λ is in microns.

Figure 5 shows a spectral sensitivity curve of the RCA 7263 vidicon. From this graph we may determine η_P' for monochromatic light for the peak of the curve A, which at 4500°A (0.45 μ) gives I_N as 27×10^{-3} μ A per μ watt. In this case, then,

$$\eta_P' \approx \frac{1.2 \times 27 \times 10^{-3}}{0.45} \approx 0.07 \approx 7\% \tag{6}$$

The mechanism by which the carriers recombine in a photoconductor is responsible, when using a vidicon tube at low light levels, for an undesirable persistance of the photoconductance existing over several television frames. This "time lag" increases as the illumination decreases and, consequently, η_P increases with decreased illumination. However, for simplicity, this function of η_P is neglected in the following calculations since the operating target voltage also has a considerable effect on η_P and may be arbitrarily selected.

If an electrical current were a steady flow of electrons evenly spaced in time it would be theoretically conceivable to cancel the effect of the dark current completely by electronic means so that even the smallest signal current could be detected. However, the number of electrons which flow in a constant electrical current during a given time interval deviates in a random manner from the number which is flowing during any other equal time interval. It is customarily assumed that these fundamental irregular statistical fluctuations in the number of electrons deviate from the average number as in a Poisson distribution. This may be applied here for the dark current in the vidicon even if we assume ideal conditions.

It may be of theoretical interest to derive an approximation for the limiting conditions for detection of the radiation from a celestial body if all the resolution elements should have exactly the same value of dark conductivity and all noise sources may be neglected except the random fluctuations in the number of electrons constituting the dark current.

If we call e_D' the average number of electrons per second constituting the dark current, I_D in μamp, through the load resistor, we may write

$$e_D' = 0.624 \times 10^{13} I_D \tag{7}$$

and for the average number of electrons e_D comprising the dark current for any resolution element, for the time the scanning beam remains on that element, we have

$$e_D = \frac{e_D'}{f_r \; R_V} \tag{8}$$

where $f_r = \frac{1}{t_f}$ and is the scanning frame repetition rate per sec and R_V is the number of resolution elements scanned during each frame. In accordance with statistics, we assume the standard deviation of e_D is $e_D^{\frac{1}{2}}$. Then, during the time the scanning beam remains on one resolution element, the radiation from the celestial body produces an average number of electrons e_S through the load resistor for each resolution element covered by the image of the celestial body and we may write for the signal to noise ratio δ_C by neglecting all noise sources other than e_D

$$\delta_C = \frac{e_S}{(e_D)^{\frac{1}{2}}} \tag{9}$$

Solving Eq (9) for e_S and substituting e_D from Eq (8) and then e_D' from Eq (7), we find

$$\begin{aligned} e_S &= \left(\frac{e_D'}{f_r \; R_V}\right)^{\frac{1}{2}} \delta_C \\ &\approx \frac{2.5 \times 10^6 \, I_D^{\frac{1}{2}} \, \delta_C}{f_r^{\frac{1}{2}} \, R_V^{\frac{1}{2}}} \end{aligned} \tag{10}$$

For the average number of quanta of light q_V arriving at the focal plane for each resolution element during the scanning time interval we may write

$$q_V = \frac{Q_M}{f_r \quad R_C} = \frac{e_S}{\eta_P} \tag{11}$$

where η_P changes with the color temperature of the source, Q_M is the number of quanta of light per second at the focal plane supplied by the celestial body and R_C is the number of vidicon resolution elements onto which the image of the celestial body is focused. By substituting Eq (11) into Eq (10) we may further write

$$\eta_P \frac{Q_M}{f_r \quad R_C} = \frac{2.5 \times 10^6 \; I_D^{\frac{1}{2}} \; \delta_C}{f_r^{\frac{1}{2}} \; R_V^{\frac{1}{2}}} \tag{12}$$

We may solve this for Q_M;

$$Q_M \approx \frac{2.5 \times 10^6 \; I_D^{\frac{1}{2}} \; \delta_C \; R_C \; f_r^{\frac{1}{2}}}{\eta_P \; R_V^{\frac{1}{2}}} \tag{13}$$

In another paper by the author (Ref. 3) the following equation expressing the relationship between the apparent magnitude number M of a celestial source with a radiation having a spectral distribution similar to sunlight (λ 0.29 to 1.45 μ) and Q_M was derived:

$$Q_M \approx \frac{6.8 \times 10^{10} \; d_T^2 \; \eta_T}{2.512^M} \tag{14}$$

where d_T is the diameter of the telescope in meters and η_T is the telescope transmission efficiency. Using this value of Q_M in Eq (13) we find,

$$\frac{6.8 \times 10^{10} \; d_T^2 \; \eta_T}{2.512^M} = \frac{2.5 \times 10^6 \; I_D^{\frac{1}{2}} \; \delta_C \; f_r^{\frac{1}{2}} \; R_C}{\eta_P \; R_V^{\frac{1}{2}}} \tag{15}$$

and from this we find for the apparent magnitude number M_V by making the most optimistic assumptions

$$M_V \approx 2.5 \log \frac{2.7 \times 10^4 \; d_T^2 \; \eta_T \; R_V^{\frac{1}{2}} \; \eta_P}{I_D^{\frac{1}{2}} \; \delta_c \; R_c \; f_r^{\frac{1}{2}}} \tag{16}$$

Equation (16) does not take into consideration the statistical differences in the value of the resistance for different resolution elements, nor does it take into account inhomogeneities in the photosensor or the noise produced by the load resistor, which will be shown later to be the practical limiting factor. Therefore, Eq (16) is of theoretical interest only; it contains the most optimistic assumptions, and thus gives a value of M_V which under no circumstances can be achieved. It should serve to prevent some unrealistic speculations in this field of endeavor.

Example 1: If

$d_T = 0.25$ meter ; $\eta_T = 0.5$; $R_V = 2 \times 10^5$; $I_D = 0.08 \mu Amp.$; $R_c = 25$;
$f_r = 30$; $\delta_c = 5$; $\eta_P = 0.05$

$$M_V \approx 2.5 \log \frac{2.7 \times 10^4 \times 0.25^2 \times 0.5 \times (2 \times 10^5)^{\frac{1}{2}} \times 0.05}{(0.08)^{\frac{1}{2}} \times 5 \times 25 \times 30^{\frac{1}{2}}}$$

$$\approx 5$$

Equation (16) can easily be modified to obtain the most optimistic apparent magnitude number M_B of a celestial body that can be detected in the daytime, when the current caused by the luminescence of the sky cannot be neglected. For such a situation, we may rewrite Eq (16) by adding to the term I_D the current I_B , in μA , which is caused by the radiation from the luminescent sky background.

Hence

$$M_B \approx 2.5 \log \frac{2.7 \times 10^4 \; d_T^2 \; \eta_T \; R_V^{\frac{1}{2}} \; \eta_P}{(I_D + I_B)^{\frac{1}{2}} \; \delta_C \; R_C \; f_r^{\frac{1}{2}}} \qquad (17)$$

The value of I_B in Eq (17) can be obtained from the light transfer characteristic curve, however a correction to account for a different color temperature may be necessary. Using the vidicon for detection of the radiation from a source against a highly luminescent background for a given target bias voltage, the effective illumination E at the focal plane of the telescope must be kept low enough to prevent saturation of the vidicon. The illumination E in footcandles at the focal plane of a telescope, for a given brightness B_B in footlamberts of the background, is determined by the well known equation

$$E = 0.25 \; B_B \frac{d_T^2}{f_T^2} \; \eta_T \qquad (18)$$

where f_T is the focal length of the telescope in the same dimensions as d_T .

Further, since one foot-candle of sunlight (between λ ' $0.29\,\mu$ and $1.45\,\mu$) comprises about 3×10^{11} quanta per mm^2 second, we may write for I_B in μA, caused by the sky background radiation, for which we assume the same spectral distribution as sunlight:

$$\begin{aligned} I_B &\approx \frac{3 \times 10^{11} E \; A_V \; \eta_P}{0.624 \times 10^{13}} \\ &\approx 4.8 \times 10^{-2} E \; A_V \; \eta_P \end{aligned} \qquad (19)$$

Substituting E from Eq (18) we find

$$\begin{aligned} I_B &\approx 4.8 \times 10^{-2} \times 0.25 \; B_B \frac{d_T^2}{f_T^2} \; \eta_T \; A_V \eta_P \\ &\approx 1.2 \times 10^{-2} \; B_B \frac{d_T^2}{f_T^2} \; \eta_T \; A_V \; \eta_P \end{aligned} \qquad (20)$$

When I_D is small in comparison to I_B, and therefore may be neglected, we find by using Eq (20) in Eq (17) for the most optomistic apparent magnitude number M_B' that can be detected,

$$M_B' \approx 2.5 \log \frac{2.7 \times 10^4 \, d_T^2 \, \eta_T \, R_V^{\frac{1}{2}} \, \eta_P}{\left(1.2 \times 10^{-2} \, B_B \frac{d_T^2}{f_T^2} \, \eta_T \, A_V \, \eta_P\right)^{\frac{1}{2}} \delta_C \, R_C \, f_r^{\frac{1}{2}}}$$

$$\approx 2.5 \log \frac{2.5 \times 10^5 d_T \, f_T \, \eta_T^{\frac{1}{2}} \, \eta_P^{\frac{1}{2}} \, R_V^{\frac{1}{2}}}{A_V^{\frac{1}{2}} \, \delta_C \, R_C \, f_r^{\frac{1}{2}} \, B_B^{\frac{1}{2}}} \qquad (21)$$

Example 2: A 10" telescope with a focal length of 75 cm is used, assume

$\eta_T = 0.5$; $\eta_P = 0.05$; $R_V = 2 \times 10^5$; $A_V = 120 \text{ mm}^2$

$\delta_C = 5$; $R_C = 15$; $f_r = 30$ frames/sec.; $B_B = 1000$ foot-lambert

If we neglect the dark current, we may use Eq (21) for finding the most optimistic value of the apparent magnitude number of the celestial body that can be detected for the given conditions. It is

$$M_B' \approx 2.5 \log \frac{2.5 \times 10^5 \times 0.25 \times 0.75 \times 0.5^{\frac{1}{2}} \times 0.05^{\frac{1}{2}} \times (2 \times 10^5)^{\frac{1}{2}}}{120^{\frac{1}{2}} \times 5 \times 15 \times 30^{\frac{1}{2}} \times 1000^{\frac{1}{2}}}$$

$$\approx 3.4$$

In practice, one of the most serious limitations for detection with the vidicon is the noise voltage produced by the load resistor through which the signal current from the target electrode flows. To achieve detection of the radiation from a celestial body, the voltage across the load resistor caused by the signal current must be greater than the inherent noise voltage of the load resistor. The noise voltage V_R of any resistor or conductor may be calculated by the well known equation:

$$V_R = 2\ (K'\ T\ f_\Delta\ R_L)^{\frac{1}{2}} \tag{22}$$

where K' = Boltzmann's constant = 1.38×10^{-23} joule/degree

T = Temperature of the load resistor R_L in degrees Kelvin

f_Δ = Bandwidth in cycles per sec.

R_L = Effective resistance of load in ohms

The momentary signal voltage V_S , we may write as

$$V_S = i_S R_L \tag{23}$$

where i_S is the mometary signal current in Amps during the effective time the scanning beam remains on each resolution element. Since one Amp = 0.624×10^{19} electrons per second we may write for i_S

$$i_S = \frac{e_S}{0.624 \times 10^{19}\ t_V} \tag{24}$$

where t_V is the time in seconds that the scanning beam appears to remain on one resolution element. The approximation for t_V will be assumed to be

$$t_V \approx \frac{1}{R_V\ f_r} \approx \frac{f_r}{f_L^2} \tag{25}$$

where f_L is the horizontal line scanning frequency in $sec.^{-1}$ We may write of Eq (23) using Eq (24)

$$V_S \approx \frac{e_S}{0.624 \times 10^{19}\ t_V} R_L \tag{26}$$

and, by substituting Eq (11) in Eq (26)

$$V_S \approx \frac{Q_M \ \eta_P \ R_L}{0.624 \times 10^{19} \ t_V \ f_r \ R_C} \tag{27}$$

Using Eq (14) in Eq (27) results in

$$V_S \approx \frac{6.8 \times 10^{10} \ d_T^2 \ \eta_T \ \eta_P \ R_L}{2.512^M \times 0.624 \times 10^{19} \ t_V \ f_r \ R_C} \tag{28}$$

Introducing δ_{SN} as the ratio between the signal voltage V_S and the noise voltage V_N we may write, by using Eqs (22) and (28),

$$\delta_{SN} = \frac{V_S}{V_N} \approx \frac{V_S}{V_R} \approx \frac{\dfrac{6.8 \times 10^{10} \ d_T^2 \ \eta_T \ \eta_P \ R_L}{2.512^M \times 0.624 \times 10^{19} \ t_V \ f_R \ R_C}}{2(K \ T \ f_\Delta \ R_L)^{\frac{1}{2}}} \tag{29}$$

and, by substituting for the Boltzmann's constant K' its numberical value in Eq (29), we find, for the most optimistic signal to noise ratio δ_{SN}

$$\delta_{SN} \approx \frac{1.5 \times 10^3 \ d_T^2 \ \eta_T \ \eta_P \ R_L^{\frac{1}{2}}}{2.512^M \ T^{\frac{1}{2}} \ f_\Delta^{\frac{1}{2}} \ t_V \ R_C \ f_r} \tag{30}$$

One should note that R_L in Eq (30) has an exponent of 1/2. We may solve Eq (30) for M which we will call the limiting apparent magnitude M_L determined by the noise voltage of the load resistor. It is

$$M_L \approx 2.5 \log \frac{1.5 \times 10^3 \ d_T^2 \ \eta_T \ \eta_P \ R_L^{\frac{1}{2}}}{R_C \ f_r \ T^{\frac{1}{2}} \ f_\Delta^{\frac{1}{2}} \ t_V \ \delta_{SN}} \tag{31}$$

Example 3: A vidicon is used with a ten inch telescope for detection of celestial bodies. The load resistor R_L connected to the signal electrode is 50,000 ohms and is cooled to a temperature of approximately 78°K with liquid nitrogen. The equivalent input noise resistance of the video amplifier is low and will be neglected; this

is also the case for the dark current and it's noise component. Further, the limitations imposed by the inhomogeneities in the photoconductive layer will be neglected; it will be assumed that the signal from the image of the celestial body is sufficient to be discriminated against the permanent signal caused by these inhomogeneities. Then assuming f_r = 30 frames per second, f_L = 15,750 cps, and using Eq (25) we find,

$$t_V \approx \frac{30}{15750^2} \approx 10^{-7}$$

Further, assuming η_P = 0.05, f_Δ = 4 Mcps, R_C = 25, δ_{SN} = 5, η_T = 0.5, Eq (31) gives, for the limiting apparent magnitude number as determined by the noise of the load resistor R_L,

$$M_L \approx 2.5 \log \frac{1.5 \times 10^3 \times 0.25^2 \times 0.5 \times 0.05 \times 50000^{\frac{1}{2}}}{25 \times 30 \times 78^{\frac{1}{2}} \times (4 \times 10^6)^{\frac{1}{2}} \times 10^{-7} \times 5}$$

$$\approx 4.7$$

Then, for any other telescope with a given lens diameter d_t' instead of d_t we find for the resulting limiting apparent magnitude number M_L'

$$M_L' = M_L + \frac{\log\left(\frac{d_T'}{d_T}\right)^2}{\log 2.512} \tag{32}$$

If we use the Mt. Palomar 200-inch telescope instead of the 10-inch telescope used in the previous calculations we get

$$M_L' \approx 4.7 + \frac{\log\left(\frac{200}{10}\right)^2}{0.4} \approx 11.2$$

The sensitivity of the vidicon may be improved by employing one or more image intensifier stages between the lens system and the vidicon face plate. If the Westinghouse Astrocon, with a light flux gain V_I of 5,000, is used and it is assumed that the light coupling efficiency factor η_I between the Astrocon phosphor screen and the face plate of the vidicon is 0.05, a net gain of 250 is attained. Then M_g, which is the theoretical gain that may be added to M_L, can be calculated by

$$M_g = \frac{\log(V_I\ \eta_I)}{\log 2.512} = 2.5 \log\left(V_I\ \eta_I\right) \qquad (33)$$

In this case

$$M_g = 2.5 \log\left(5000 \times 0.05\right) \approx 6$$

and the limiting magnitude for the ten inch telescope in Example 3 becomes $4.7 + 6 = 10.7$, if the sky background and the inherent background of the intensifier may be neglected. If, instead of conventional optical arrangements, fiber optics are used between the Astrocon and the vidicon, a further gain of 10 in the light flux might be obtained, which then gives a total for M_g of 8.5 resulting in a limiting magnitude of 13.2 instead of 10.7. However, when calculations are made for the use of intensifiers, as in Eq (32), care must be taken not to violate quantum mechanical considerations. Obviously, under any circumstances and for any source, the ultimate limit in detection is theoretically reached when only one photoelectron per resolution element is released during the observation time.

To determine whether a vidicon system used with an image intensifier having a light flux gain of 5,000 and using fiber optical coupling is really capable of detecting a celestial body of 13.2 apparent magnitude employing a ten inch telescope, we must first determine the number of quanta of light available at the focal plane. Using

Eq (14) we find the average number of quanta of light per sec arriving at the photocathode of the intensifier from the celestial body:

$$Q_M \approx \frac{6.8 \times 10^{10} \times 0.25^2 \times 0.5}{2.512^{13.2}} \approx 11000$$

As described before, the scanning mechanism of the vidicon effectively divides the photoconductor into separate resolution elements R_V and hence results in R_C for the star image, and the same number of resolution elements R_V and R_C are here effective for the photosensor of the intensifier. Further, the effective exposure time t_e, ignoring any persistance of the output phosphor of the intensifier, is determined by the scan frame rate of the vidicon and is $\frac{1}{f_r}$. Thus we find for the 10" telescope and the 13.2 magnitude by using Eq(11) the number of quanta of light per resolution element arriving from a celestial body at the intensifier photocathode during the effective exposure time t_e

$$q_V = \frac{Q_M}{f_r \;\; R_C} \approx \frac{11000}{30 \times 25} \approx 15$$

Since the quantum efficiency of the photosensor of the intensifier η_c is only in the order of 4 per cent we find it impossible that detection of a celestial body of 13.2 apparent magnitude could occur under the assumed conditions. $M_g = 8.5$ as calculated by Eq (33) added to M_L gives an undetectable star magnitude for this arrangement; also sky background and photocathode dark current emission has to be considered. The limitations imposed by unavoidable statistical flucuations when sufficient image intensification is used before the pickup tube have been treated by the author in another paper (Ref 7). The simplified equation found there for the ultimate magnitude number M_{opt} for a celestial body radiating light with a spectral composition similar to sunlight (λ 0.29 μ to 1.45 μ) that can be detected is:

$$M_{opt} \approx 2.5 \log \frac{6.8 \times 10^{10} \; d_T^2 \; \eta_T \; \eta_C^{\frac{1}{2}} \; R_I^{\frac{1}{2}} \; t_e^{\frac{1}{2}}}{\delta_I \; R_C \left(Q_B + 3 \times 10^{11} E_D\right)^{\frac{1}{2}}} \tag{34}$$

where R_I is the selected number of resolution elements per mm^2 of the intensifier photocathode as determined by the number of effective resolution elements of the vidicon target section, and δ_I is the ratio between the average number of electrons for each effective resolution element caused by radiation from the celestial body and the standard deviation of the intensifier photocathode emission for each resolution element caused by the background radiation plus the effective photocathode dark current emission; the probability p to detect a celestial body is a function of δ_I.

Q_B is the number of quanta of light per mm^2 sec arriving from the sky background at the focal plane (radiation similar to sunlight λ 0.29μ to 1.45 μ). By using Eq (18) Q_B is

$$Q_B \approx 7.5 \times 10^{10} \left(\frac{d_T}{f_T}\right)^2 B_B \; \eta_T \tag{35}$$

In Eq (34) E_D is the flux of light in footcandle (sunlight) that would have to be focused onto the photocathode of the intensifier tube causing a photoemission equivalent in its effect to the inherent background effects of the tube. Eq (34) is only valid where

$$\frac{Q_M \; \eta_C \; t_e}{R_C} \geqq \delta_I \geqq 1 \tag{36}$$

because of δ_I and since at least one photoelectron must be released to make detection theoretically possible.

For the cases where Eq (36) is not fulfilled, therefore making Eq (34) unusable, the theoretically ultimate limiting apparent magnitude number M_t, that is

the magnitude number resulting in an average of one electron for each resolution element covered by the star image during the selected exposure time, may be computed by using Eq (14) and rewriting Eq (36); it is

$$M_t = 2.5 \quad \frac{6.8 \times 10^{10} d_T^2 \, \eta_T \, \eta_C \, t_e}{R_C} \tag{37}$$

The necessary gain of the intensifier to make the results of Eq (34) or (37) match those of Eq (31) may be calculated by using Eq (33). Further, one must determine, especially for twilight and daytime hours, whether the sky background radiation and the inherent background effects of the intensifier would cause saturation of the vidicon when using the available gain of the intensifier. The light flux E_I in foot-candles arriving at the vidicon face plate is

$$E_I = \left[0.25 \; B_B \left(\frac{d_T}{f_T}\right)^2 \eta_T + E_D\right] V_I \;\; \eta_I \tag{38}$$

If we wish to improve the signal to noise ratio of a conventional vidicon chain operated at 30 frames per second, a storage unit could be used, employing, for example, a Farnsworth Iatron storage tube. The signal to noise ratio will improve with the square root of the number of integrated frames, P_i . Hence, the co-efficient Z of the signal to noise improvement is

$$Z = P_i^{\frac{1}{2}} \tag{39}$$

Example 4: A Westinghouse Astrocon (WX 4342) is used before the vidicon chain of Example 3 with a 10 inch telescope, and then in connection with a 200 inch telescope, where d_T = 0.25 meter and 5 meters, η_T = 0.5, η_C = 0.4, δ_I = 5, R_C = 25, t_e = 1/30 sec, R_I = 300, $E_D \approx 10^{-8}$ foot candle, B_B = 1.5 × 10^{-4}

footlambert, and f_T = 15 meters. For the 10" telescope we use Eq (37) for determining M_t since Eq (34) for the small number of Q_B and E_D would give an incorrect magnitude number.

$$M_t \approx 2.5 \log \frac{6.8 \times 10 \times 0.25 \times 0.5 \times 0.04}{25 \times 30}$$

$$\approx 12.6$$

For the 200 inch telescope at Mt. Palomar, we find for Q_B by using Eq (35)

$$Q_B \approx 7.5 \times 10^{10} \times \left(\frac{5}{15}\right)^2 \times 1.5 \times 10^{-4} \times 0.5$$

$$\approx 6 \times 10^5 \ \frac{\text{Quanta}}{\text{mm}^2 \text{sec.}}$$

and M_{opt} for the 200 inch telescope is by using Eq (34)

$$M_{opt} \approx 2.5 \ \log \frac{6.8 \times 10^{10} \times 5^2 \times 0.5 \times 0.04^{\frac{1}{2}} \times 300^{\frac{1}{2}}}{5 \times 25 \times (6 \times 10^5 + 3 \times 10^{11} \times 10^{-8})^{\frac{1}{2}} \times 30^{\frac{1}{2}}}$$

$$\approx 16.8$$

Since the limiting apparent magnitude previously calculated for a 10 inch telescope with intensifier, where η_I = 0.5, was 13.2, and from above it was determined that M_t cannot be greater than 12.5 magnitude, it can be concluded that the amplification factor of the Astrocon using fiber optical coupling is sufficient to reach the limiting condition for the arrangement. The same is valid for using the 200 inch telescope when employing the intensifier-vidicon arrangement.

For the 200 inch telescope and fiber optical coupling (η_I = 0.5) the illumination focused onto the face plate of the vidicon because of the radiation of the night sky is

$$E_I = \left[0.25 \times 1.5 \times 10^{-4} \times \left(\frac{5}{15}\right)^2 \times 0.5 + 10^{-8}\right] \times 5000 \times 0.5 \quad \approx 5 \times 10^{-3} \text{ footcandle}$$

which would not cause saturation of the vidicon. However, for observations during twilight hours, saturation may occur. It may be of interest to note that the background of the Astrocon, quoted to be equivalent to 10^{-8} foot-candles photocathode illumination, corresponds to about 3000 quanta per mm^2 sec of sunlight.

CONCLUSION

The sensitivity of commercially available vidicons may not be sufficient in many applications for detecting weak visible radiation from celestial bodies because of inherent background effects of the tube and noise sources in connection with the instrumentation. This may be improved by using image intensifier systems between the optical system and the vidicon, integration over several fields, or by using a return beam vidicon with an electron multiplier.

APPENDIX

Description of the Experimental Vidicon Camera Arrangement

Figures 6 through 12 show the complete schematics of the vidicon chain which was constructed for this project. The horizontal line sweep frequency is variable between 9000 and 16000 lines per second, and the vertical sweep frequency between 25 and 60 fields per second. No interlacing is used, since, for observation of moving objects, no increase in resolution would be obtained by the interlacing. To avoid disturbances by the microphonics in the video amplifier and to reduce noise all frequencies lower than the horizontal line frequency are suppressed. To obtain the correct brightness levels for the reproduced background, a specially designed DC restoration circuit, later described, and a pulser are used in connection with a line shading compensator. Small coupling capacitors and compact wiring is possible in such a system. To reduce the amount of manual work, an old AN-08-30 AXT 2 - 2M Iconoscope camera was taken apart and the chassis was used for the construction of this experimental unit.

Description of the Circuitry

Figures 13, 14, and 15 show the frequency characteristic of the video amplifier. Shading effects produced by insufficient shielding from sweep and blanking circuits have to be avoided. Extremely careful shielding of the signal electrode is especially required. For the same reason the deflection system has to be arranged symmetrically with respect to ground and may also have to be well balanced with additional resistors and capacitors. The cathode potential of the vidicon is raised into the cut-off region of the tube during the retrace. Cutting off the beam during the retrace time will produce positive syncronizing pulses on the target electrode

load resistor, and will also provide leveler pulses for DC restoration. The first stages of the video preamplifier consist of a double triode where both stages are cathode coupled. The amplification factor of such stages is not quite as high as in a cascaded arrangement. However, such a cathode coupled arrangement is more simple than the cascaded, has less feed-back in the first stage, and practically the same noise factor. Also with the cathode coupled arrangement, there exists a good possibility for injection of the line shading correction voltage as explained later. The stage following the cathode coupler is a pentode since at this point the lower noise factor offered by a triode arrangement is no longer of importance.

It is very important that the gain is controlled after sufficient preamplification is obtained, otherwise if the gain is controlled in the first video stages the following stages with their high noise factor and high amplification would produce so much circuit noise that the attenuated signal would be too small compared to the noise of the following stages.

The peak amplitude of the syncronizing pulses is a function of the background brightness (Figure 16). Therefore, the lost DC component representing the background brightness level can be recovered with a properly designed diode or grid current leveler arrangement (Figures 7 and 8, V3 and V7). However, horizontal shading introduced by a time constant in the order of the time for the sweep of one line cannot be corrected by such a DC restoration circuit. Figure 17 shows the resulting distortion in the video signal. To compensate for this line shading, a corrective voltage, opposite to the shading, has to be produced from the horizontal sweep frequency and added to the video signal (Figure 7 tubes V2 and V4). Most of the schematics are self-explanatory, so that a further description should not be

necessary.

With a horizontal line frequency of 10000 lines per second and a vertical field frequency of 40 (250 line picture), the threshold of the unit using the RCA 6198 vidicon was determined to be better than $3 \cdot 10^{-3}$ foot-candle. Threshold definition: That light level at which a diagonal cross having a width of 10% of the picture size is just recognizable visually on the reproducer screen. Most of the noise in this system appears to be produced by the target load resistor, since turning the beam current in the vidicon on and off does not change the noise seen on the screen of the reproducer. The substitution of the load resistor by a so-called electrically cold resistance, produced by feedback, might be a possibility for improving the signal to noise ratio at low light levels in a vidicon pickup chain.[Ref 12.] However, since the resistance has to be maintained over a wide frequency range, the problem might be a difficult one. A return beam system with a secondary electron emission amplifier system such as the multiplier arrangement in an image orthicon would be a better and a more stable solution to overcome the noise in the load resistor.

Under threshold conditions the reproduced information appears to be "sticking" with a time constant of approximately 0.25 sec. To overcome this disadvantage at low light levels either one or more preamplifiers such as in the intensifier image orthicon will have to be used or new types of photoconductive materials will have to be developed which have less time lag at low light levels than the materials presently used in the contemporary RCA 6198 which is antimony trisulfide (Sb_2S_3). Therefore, as the final conclusion, the author of this report suggests the development of a return beam vidicon with a secondary electron emission multiplier section and if possible preamplification before the photoconductive layer.

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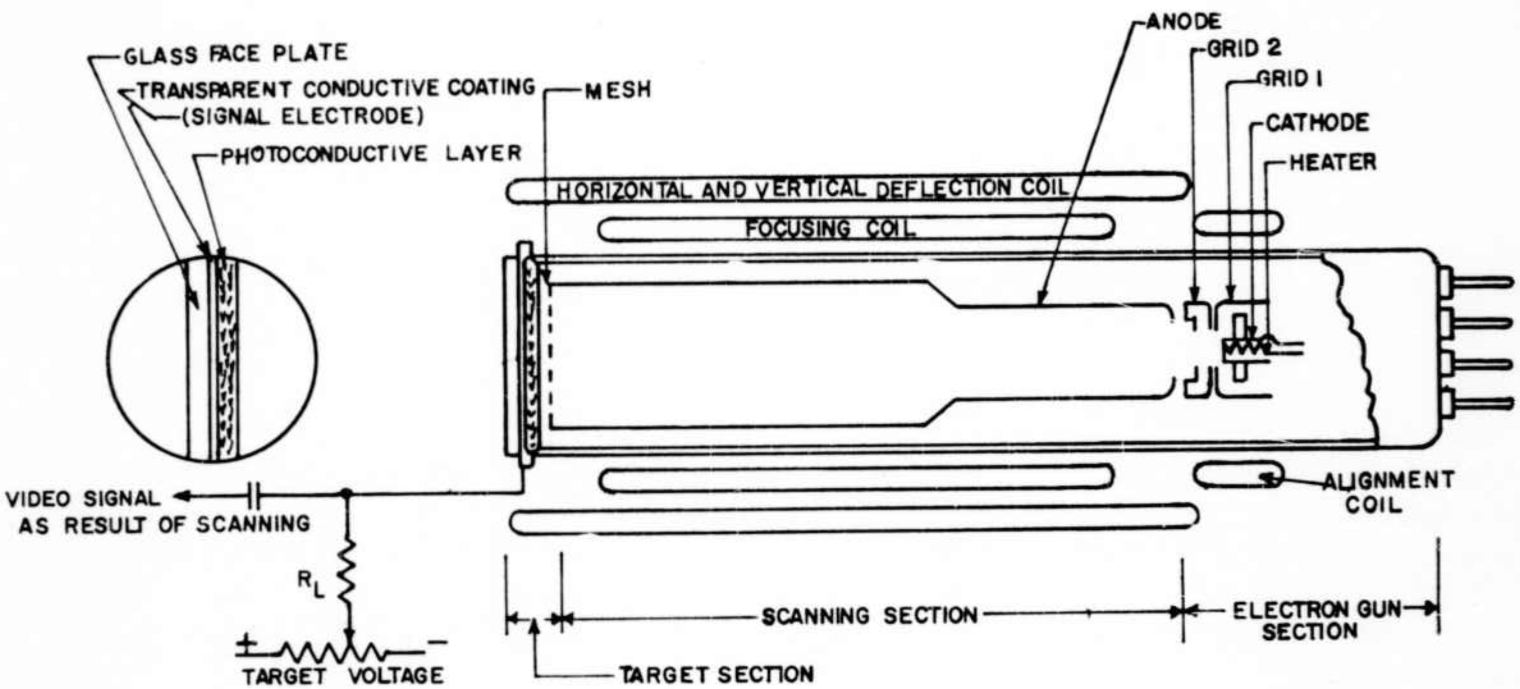

Figure 1. Schematic Arrangement of Vidicon.

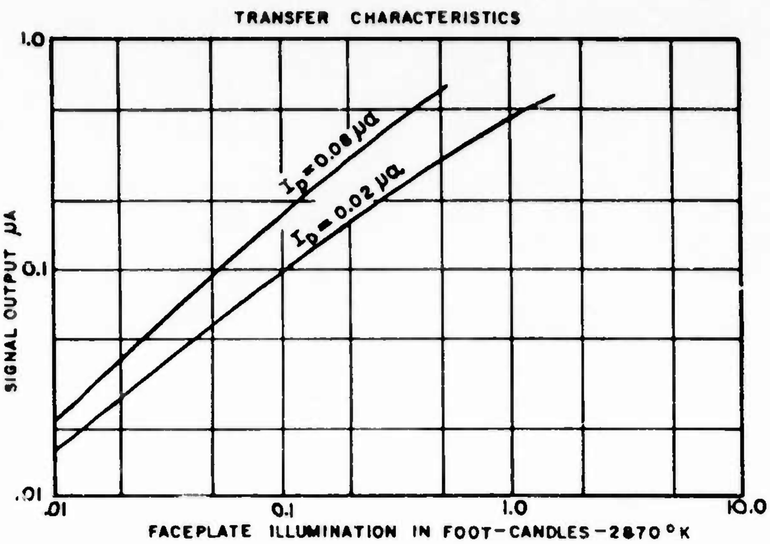

Figure 2. Light Transfer Characteristics of ML-7351

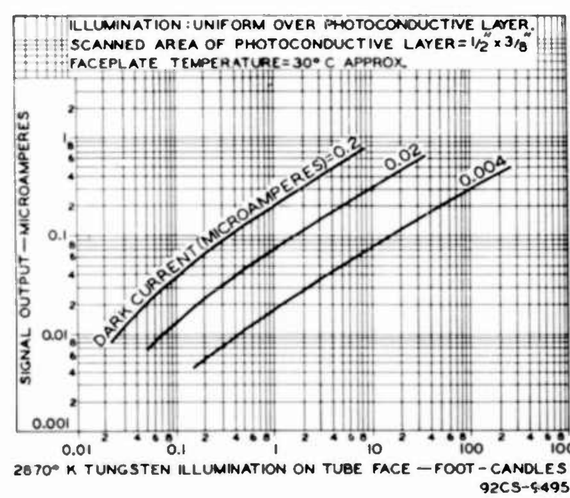

Figure 3. Light Transfer Characteristics of a Typical 7263 Vidicon.

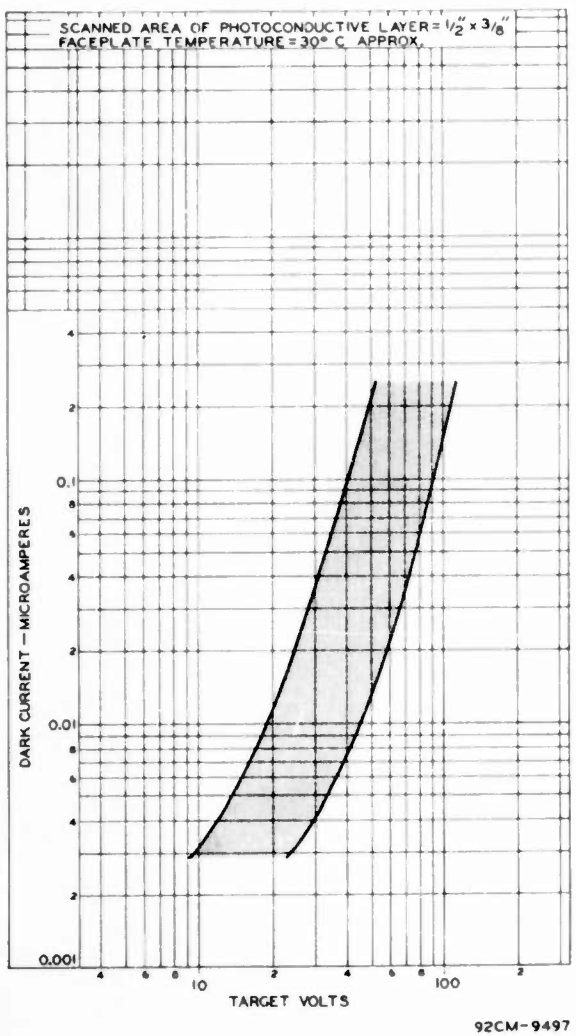

Figure 4. Range of Dark Current for Type 7263.

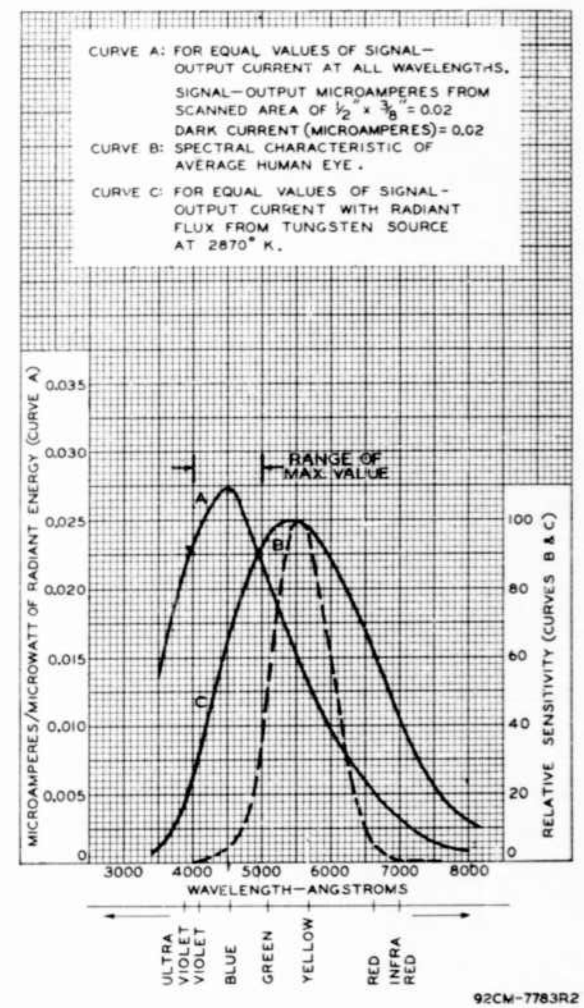

Figure 5. Spectral Sensitivity Characteristics of Type 7263.

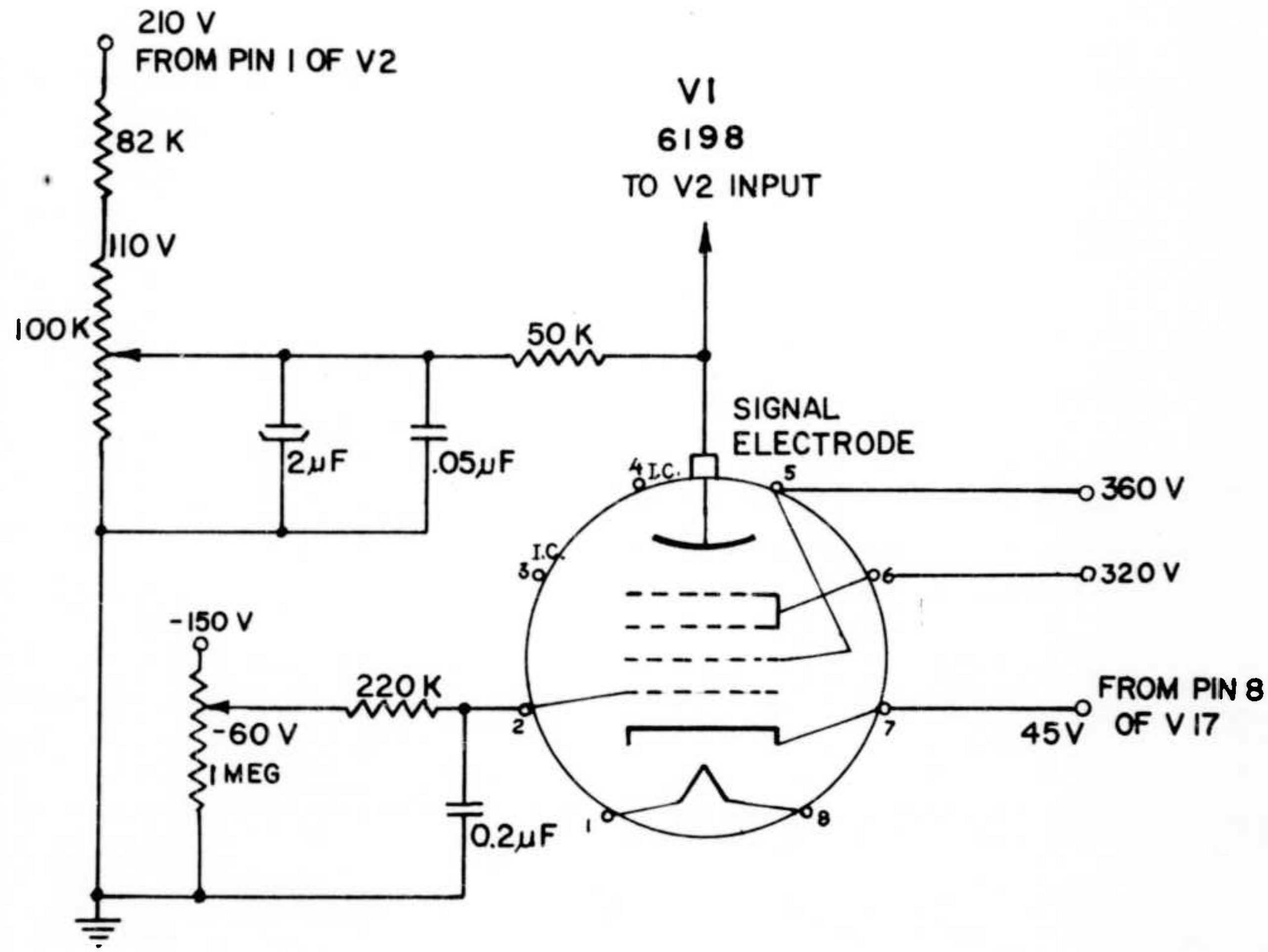

Figure 6. Vidicon Tube Connections.

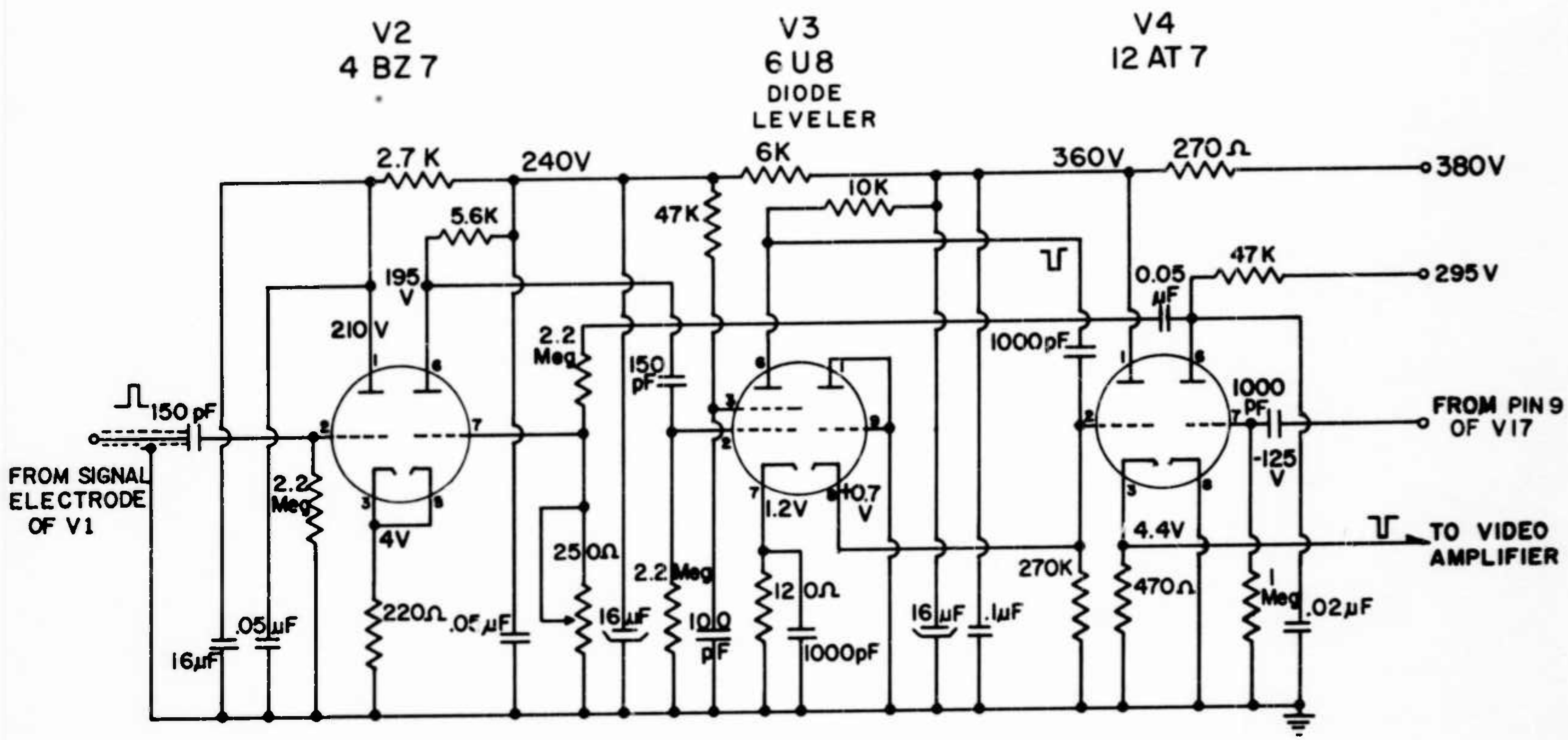

Figure 7. Video-Pre-Amplifier.

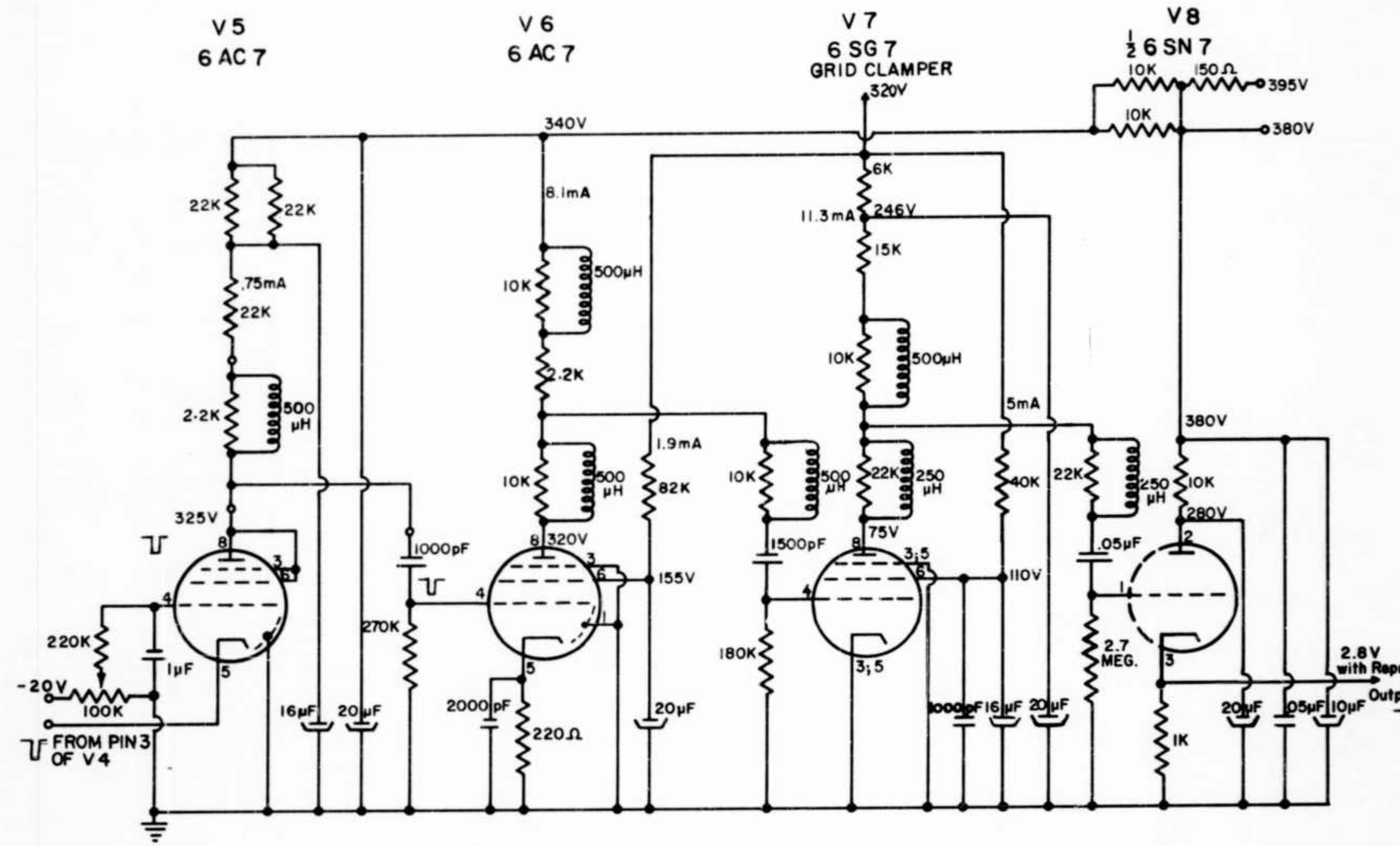

Figure 8. Video-Amplifier

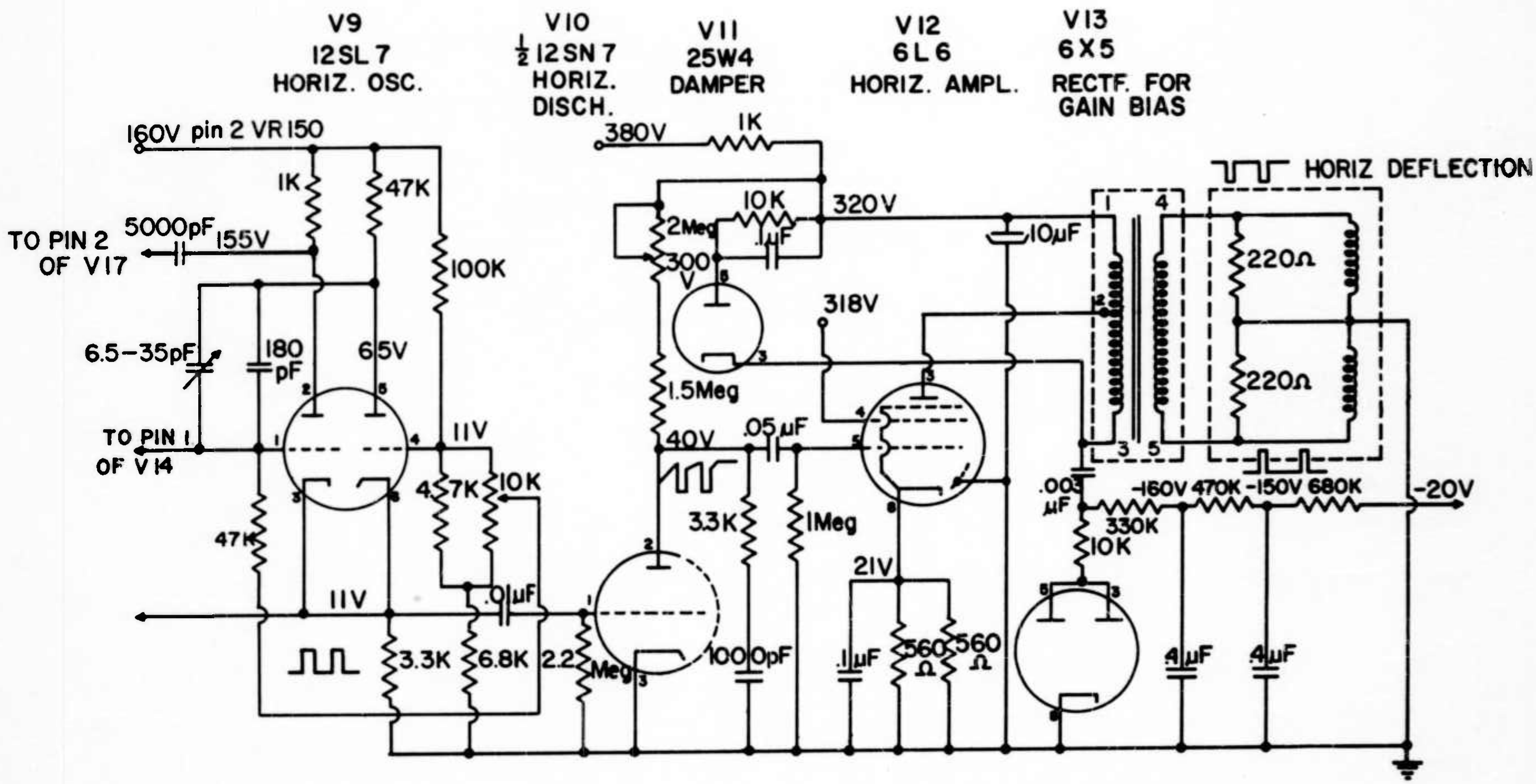

Figure 9. Horizontal Oscillator and Sweep Amplifier.

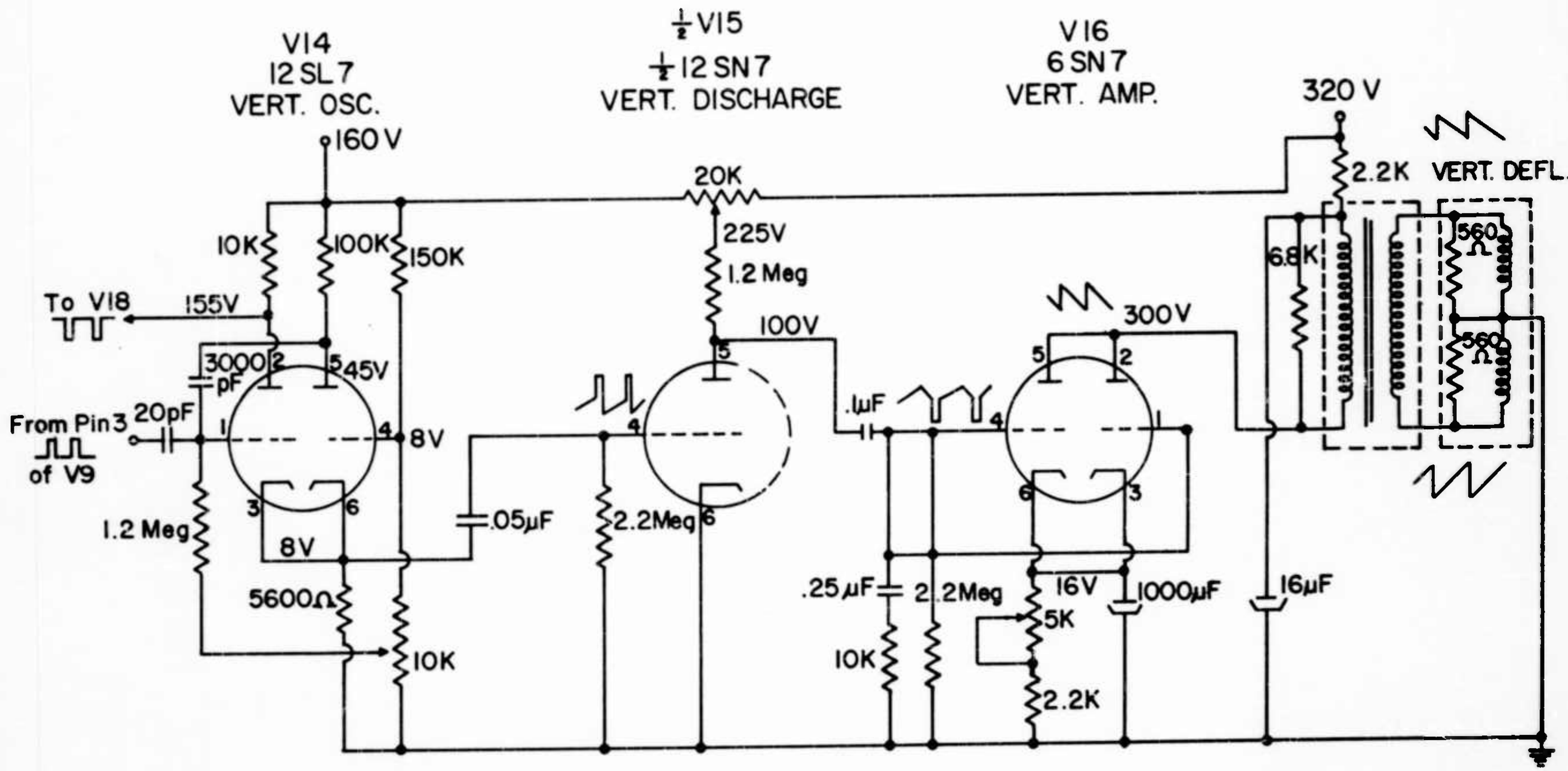

Figure 10. Vertical Oscillator and Sweep Ampflifier.

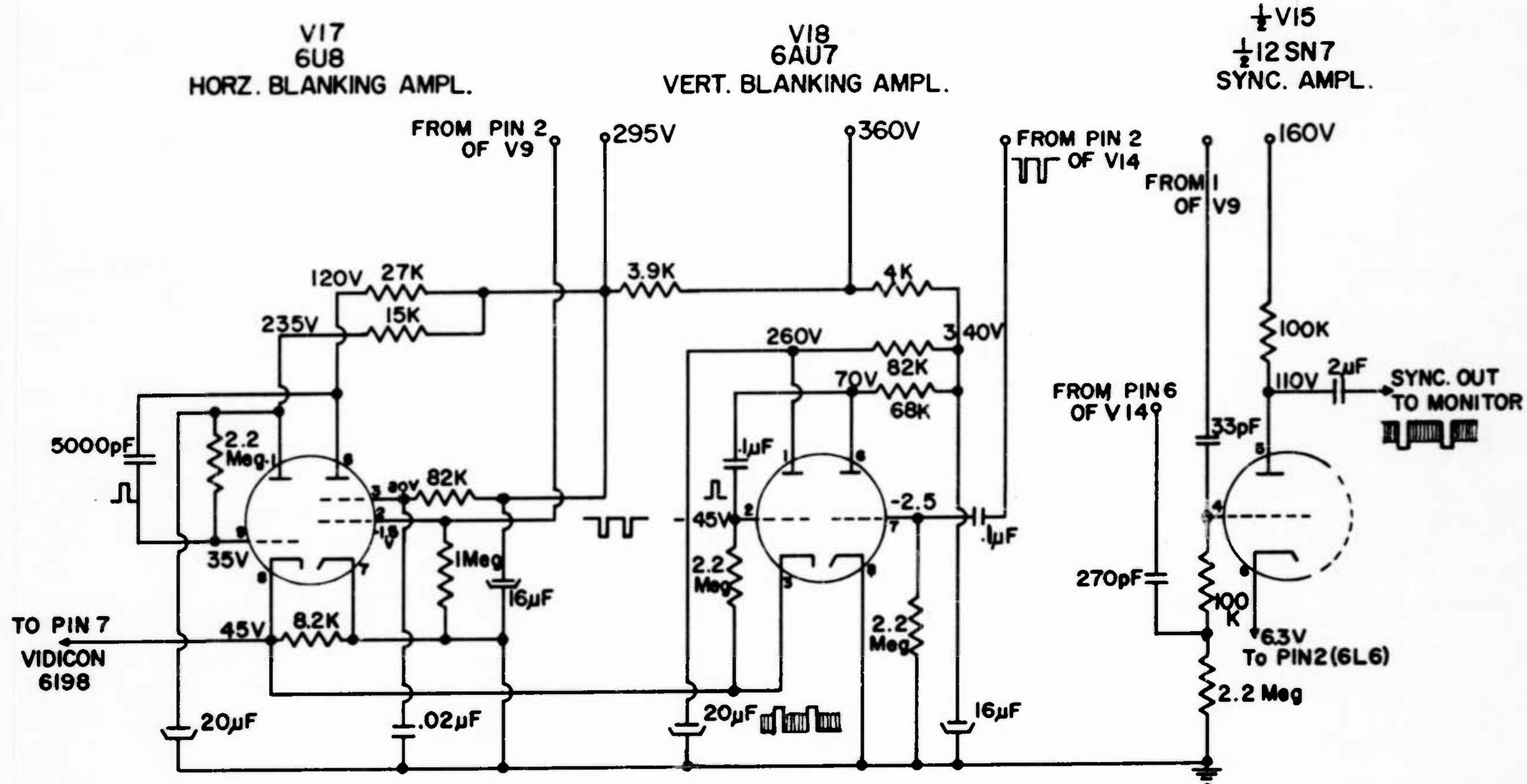

Figure 11. Blanking and Synchronization Circuits.

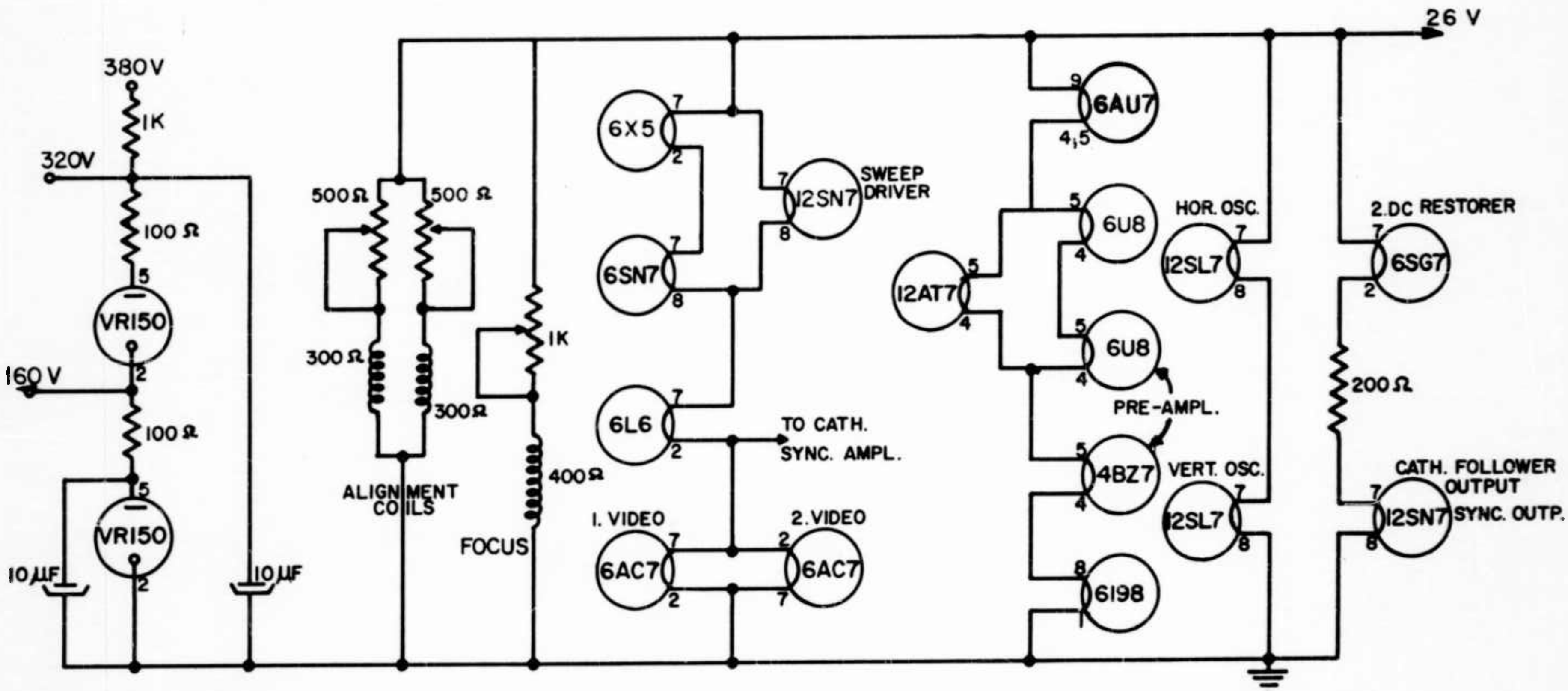

Figure 12. Filament Connection.

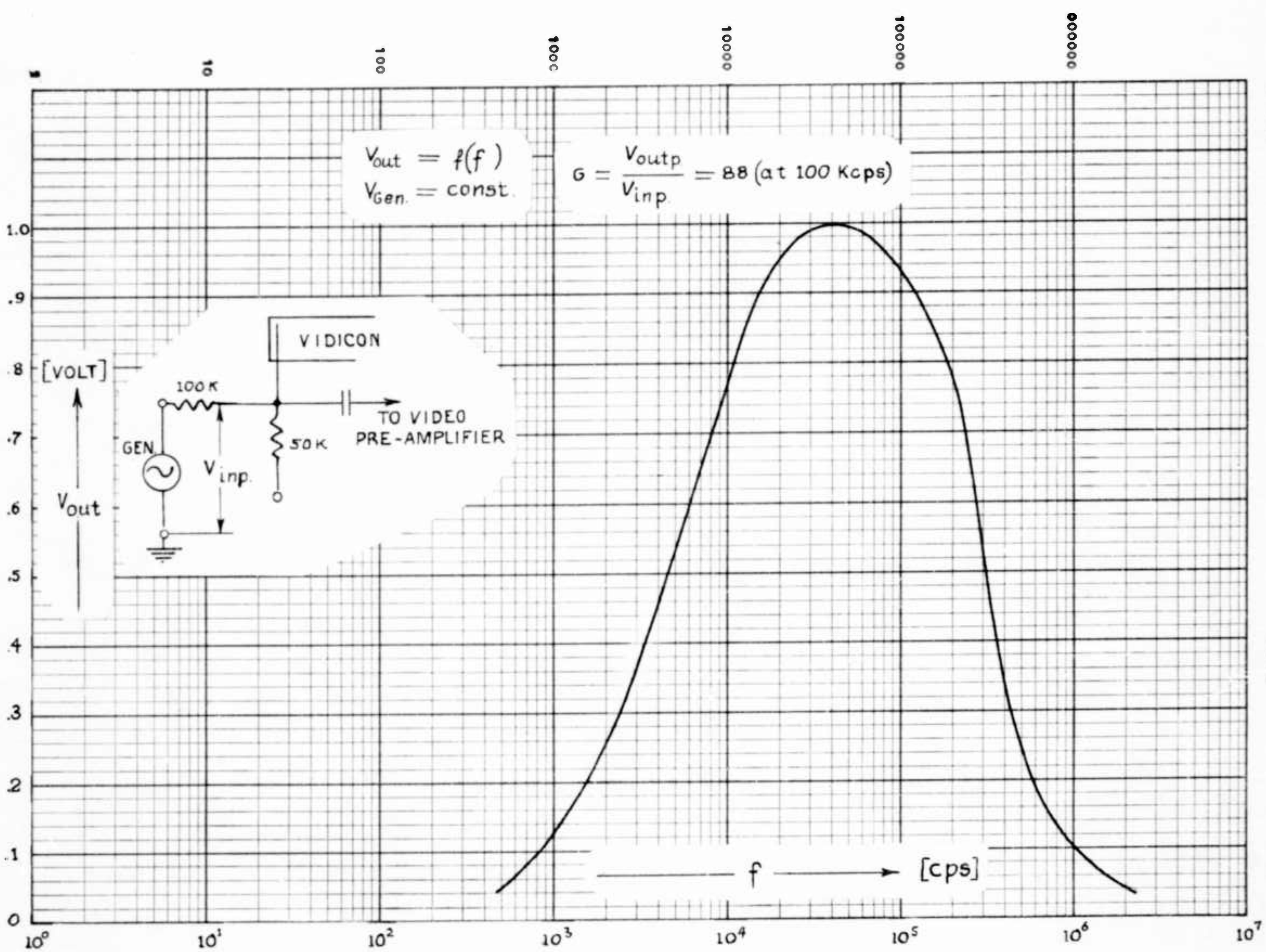

Figure 13. Frequency Characteristics Curve of Video Pre-amplifiers.

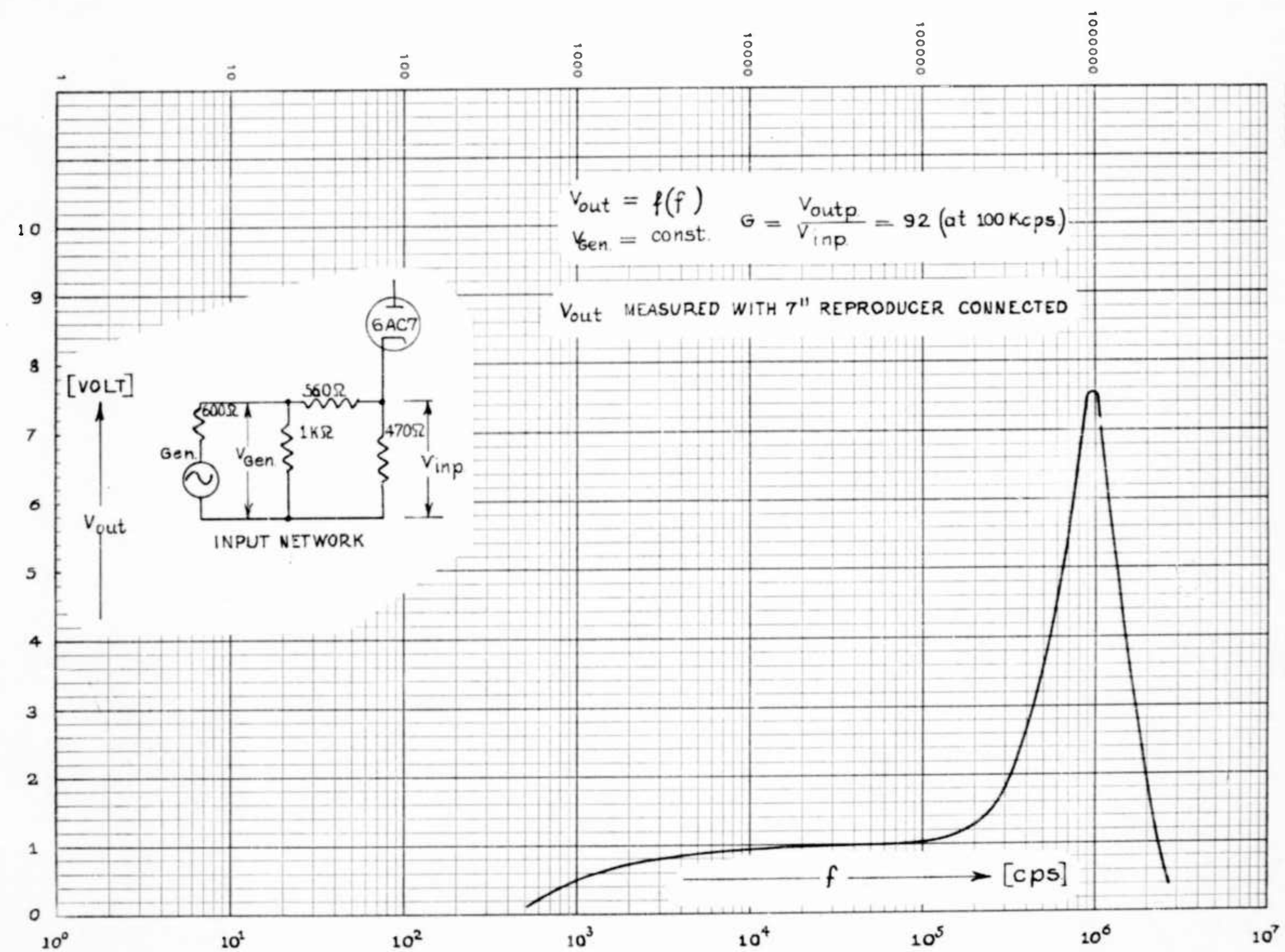

Figure 14. Frequency Characteristics Curve of Video Amplifiers.

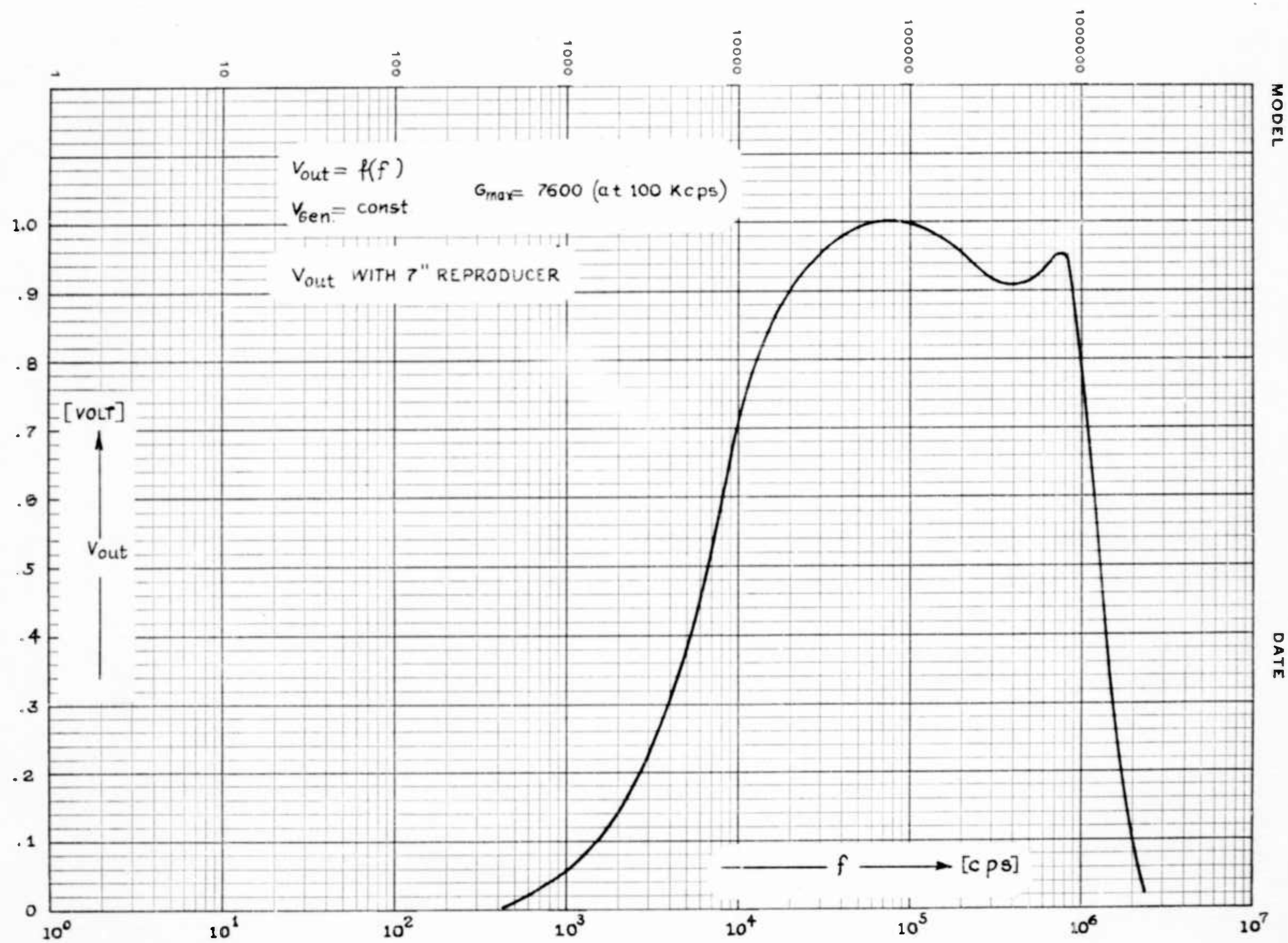

Figure 15. Over-All Frequency Characteristics Curve of Video Amplifiers.

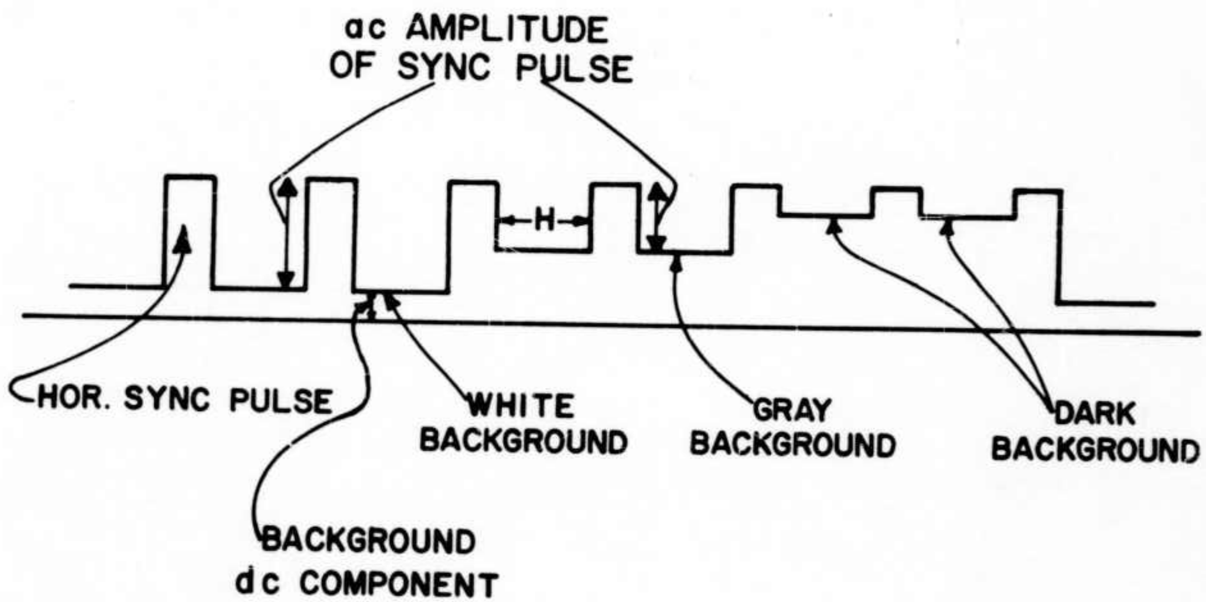

Figure Figure 16. Video Signal with dc Component.

Figure 17. Shading Introduced by Coupling Network.

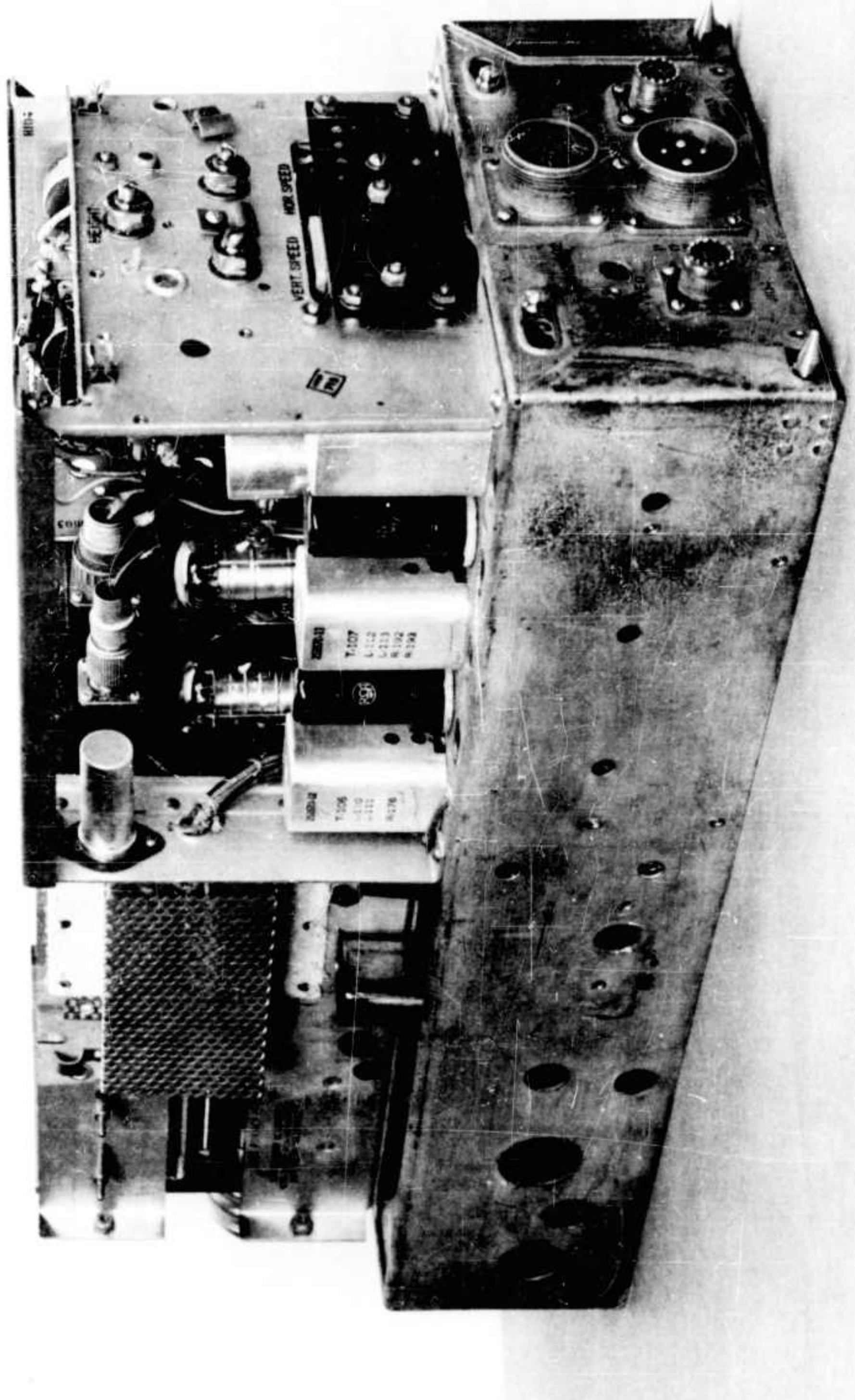

Figure 18a. Experimental Vidicon Camera as shown by Schematics in Figures 6 thru 12.

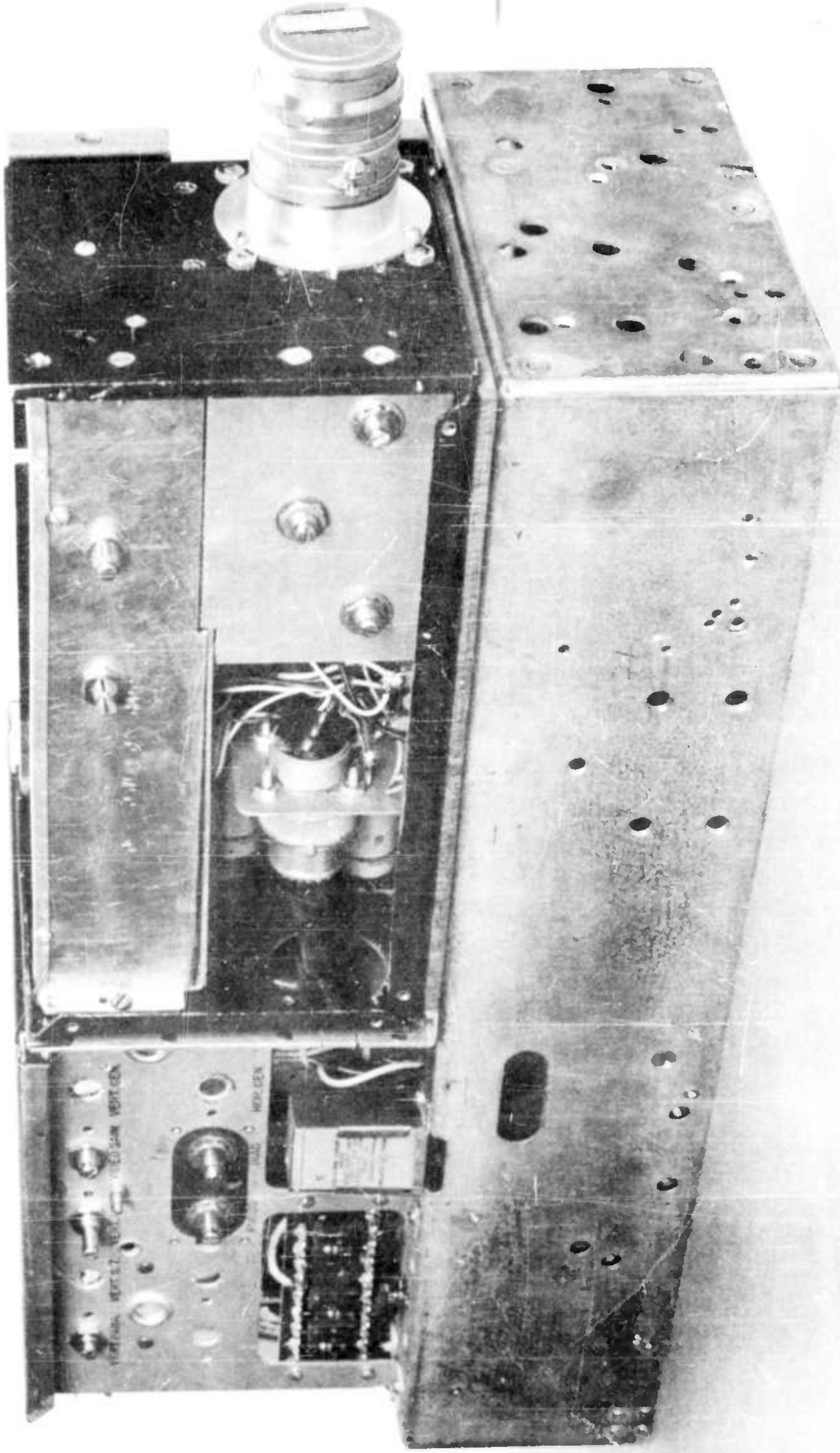

Figure 18 b. Continued

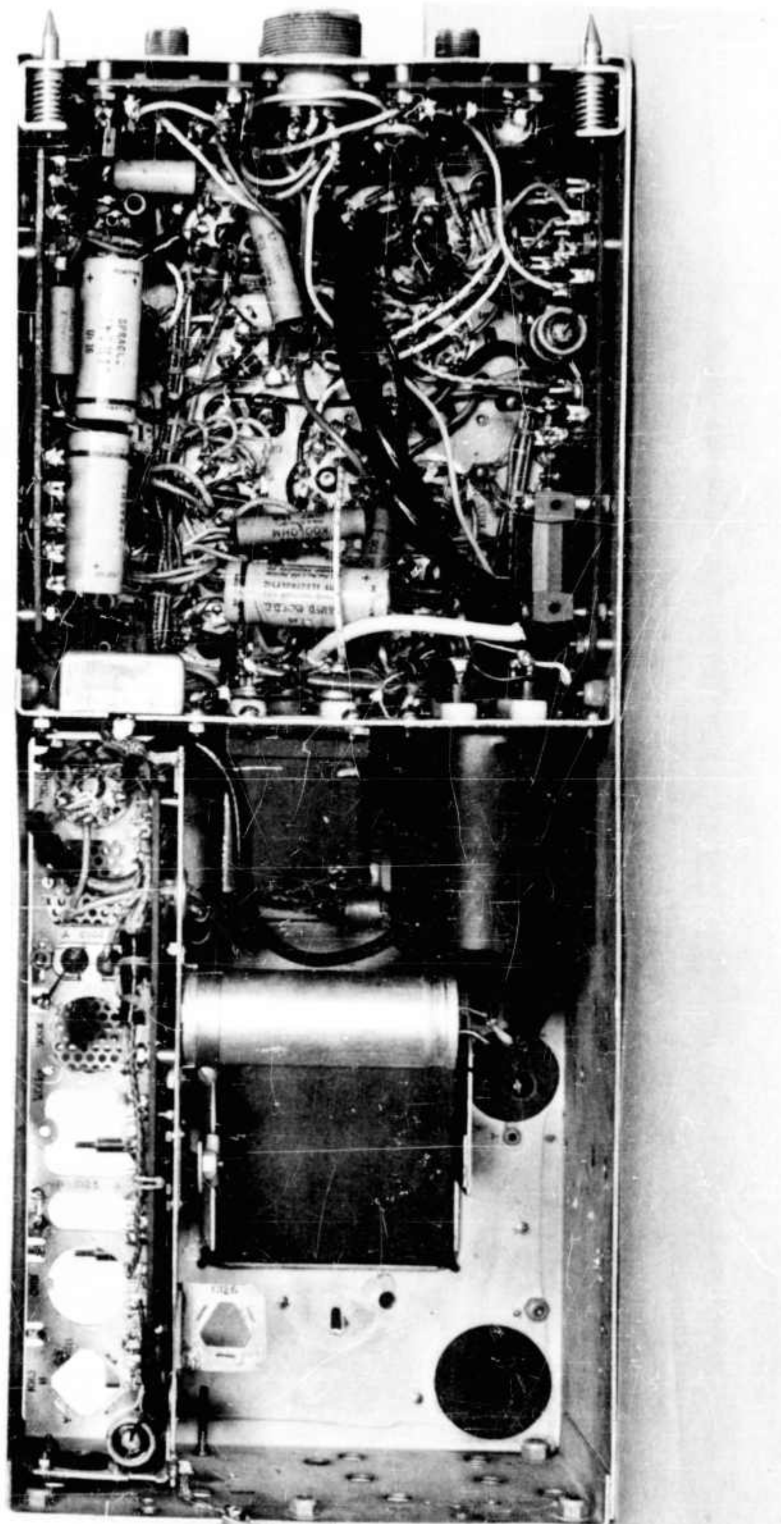

Figure 18 c. Continued.

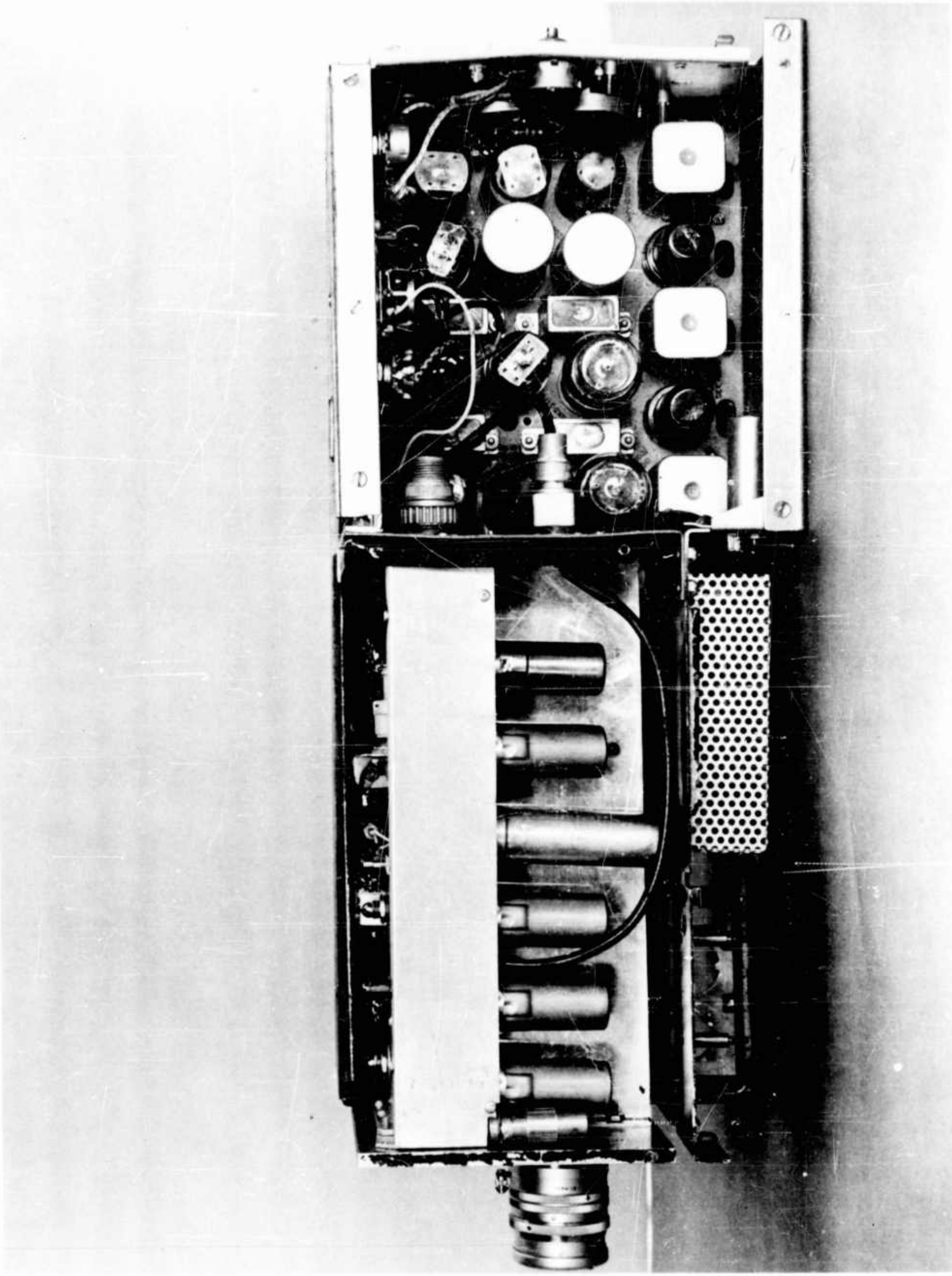

Figure 18 d. Continued

Aeronautical Research Laboratory, Wright-Patterson AFB, Ohio LIMITATIONS IN DETECTION OF CELESTIAL BODIES EMPLOYING ELECTRONICALLY SCANNED PHOTOCONDUCTIVE IMAGE DETECTORS by R. K. H. Gebel. December 1961. 45p. incl. illus. (Project 7072 and 7021; Task 70827 and 70846) (ARL 153)

Unclassified Report

Theoretical limitations in the detection of celestial bodies, by means of photoconductive sensors are investigated. Applicable simplified basic equations are derived for the maximum apparent number of a celestial body that is detectable with the

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commercially available vidicon tube (a) assuming the most optimistic conditions and (b) as determined by background radiation during the day and the night, load resistor noise and other practical limitations. The equations are extended to cover the possible gain in sensitivity obtainable by using preamplification with additional image converter type tubes, and by integration over several scanning fields. The schematics of an easily constructed very sensitive experimental vidicon system used for the investigations are appended.

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